Comparative study on calculation methods of wave force on breast wall in Chinese, Japanese and European codes

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Abstract. The stability calculation of breast wall is an important content in the design of slope marine structures. The main damage load of breast wall on rubble-mound breakwater is wave force. In the absence of physical model test data, wave force is often differently calculated according to the methods specified in the different codes and design manuals. In this paper, different calculation methods for wave force based on the codes of China, Japan, and Europe are discussed and analyzed. Then, a revetment project in Africa is taken as an example to compare the calculation results. Finally, important conclusions can be obtained that (1) the results calculated by the Chinese code are relatively reasonable; (2) When calculating the wave force imposed on breast wall placed on vertical wall, the Goda’s method in the Japanese code is practicable. As for the relevant calculation of the wave force on slope structures, it can only be used for approximate estimation. (3) In the method of BS6349, the range of K value is relatively large, which has great influence on the calculation results. When using this method, more attention should be paid to the selection of K value. The results can provide a reference for structure design of breast wall without physical model test data.

1. Introduction

The breast wall is an important component of slope marine structures such as breakwaters and revetments. Due to the location of breast wall on slope marine structures, it is often subjected to large wave force. For designing breast wall, it is important to calculate reasonable value of wave force, which influences the protection effect of breast wall and its construction cost.

In the field of analyzing wave force imposed on breast wall of slope structures, many scholars have conducted a large number of theoretical and numerical studies and physical model tests. Anand [1] et al. studied the hydrodynamics of the curved sea wall under random waves. Nørgaard [2] conducted a numerical simulation of wave force on rubble-mound breast wall of breakwaters in deep and shallow water wave conditions. By using physical model tests, Yu [3] studied the applicability of the calculation formula of wave force of breast wall on rubble-mound breakwaters proposed in "Code of Hydrology for Sea Harbour" (JTJ213-98). Li [4] explored the factors influencing the wave force on the wave-facing surface of typical breast wall through physical model tests. Guo [5] discussed the influence of wave height on the design of breast wall.

It can be seen that scholars mostly conduct relevant numerical researches and physical model tests on wave force of breast wall. Without physical model tests, it is also an important theoretical method for calculating wave force based on national codes. However, there are few comparative studies on
different calculation methods in national codes. Therefore, based on the elaboration of the principles of different calculation methods in various countries, this research systematically analyzes and compares different calculation methods for wave force on breast wall to provide a reference for structure design.

2. Calculation methods for wave force imposed on breast wall

In this section, calculation methods of wave force on breast wall in Chinese, Japanese and European codes are analyzed and discussed.

2.1. Calculation methods for wave force on breast wall in Chinese code

In the early design stage of structures, there is no relevant physical model test data. Generally, the wave force on breast wall is calculated in accordance with “Code of Hydrology for Harbour and Waterway” (JTS145-2015)[6] and then corrected according to “Code of Design for Breakwaters and Revetments” (JTS154-2018)[7].

The calculation method for wave force in “Code of Hydrology for Harbour and Waterway” (JTS145-2015)[6] is shown as follows.

\[
p = 0.24 \gamma H K_P
\]

where, \( p \) is the average wave force, kPa; \( K_P \) is the average pressure coefficient related to dimensionless parameter \( \xi \); \( h \) is the wave height, m; and \( \gamma \) is the unit weight of sea water, kN / m³.

The above method is suitable for the case of no covered blocks in front of breast wall. However, there is no corresponding formula for breast wall with covered blocks in front. Therefore, in the early design stage of breast wall, the calculation of wave force can be also based on equation (1). Just the wave force should be multiplied by a reduction factor when covered blocks are applied according to “Code of Design for Breakwaters and Revetments” (JTS154-2018) [7]. According to Article 4.3.25.1 of “Code of Design for Breakwaters and Revetments” (JTS154-2018)[7], when there are blocks or stones sheltered in front of breast wall and the blocks or stones are at least two rows, at the same time the height is enough to form a full shield, the horizontal wave force and uplift wave force acting on the breast wall can be multiplied by a reduction factor of 0.6 ~ 0.7. When calculating the stability of the reverse-L-shaped breast wall, the favorable effect of the vertical wave force shall be considered according to the “Design Manual of Harbor Engineering (Volume II)” [8].

2.2. Calculation methods for wave force on breast wall in Japanese code

The Japanese code “Technical Standards and Commentaries for Port and Harbour Facilities in Japan”[9] mainly refers to the Goda formula for the calculation of wave force.
The calculation method for wave force is shown as follows.

\[ \eta^* = 0.75(1 + \cos \beta) \lambda_1 H_D \]  

(2)

\[ p_1 = 0.5(1 + \cos \beta)(\alpha_1 \lambda_1 + \alpha_2 \lambda_2 \cos^2 \beta)\rho_0 g H_D \]  

(3)

\[ p_2 = \frac{p_1}{\cosh(2\pi h/L)} \]  

(4)

\[ p_3 = \alpha_3 p_1 \]  

(5)

where, \( \eta^* \) is the distance from the still water level (SWL) to the zero point of the wave force, m. \( P_1 \) is the wave force at the still water level, kPa. \( P_2 \) is the wave force at seabed, kPa. \( P_3 \) is the wave force at the bottom of the structure, kPa. \( \rho_0 g \) is the unit weight of the water, kN / m\(^3\). \( \beta \) is the angle between the incident wave and the normal of the vertical wall, °. \( \lambda_1 \) and \( \lambda_2 \) are the wave force correction coefficients. \( h \) is the water depth at the bottom of the structure, m. \( L \) is the wavelength corresponding to \( T_s \), m. \( H_D \) is the limited wave height, m. And \( \alpha_1, \alpha_2, \alpha_3 \) are all coefficients.

2.3. Calculation methods for wave force on breast wall in European Code

The Jessen (1984) and Bradburyeral (1988) methods, Pedersen methods in “CIRIA C683 The Rock Manual”[10], as long as the relevant methods in the BS6349-7 “Guide for Design And Construction of Breakwater”[11] are the main methods used in European countries for the calculation of wave force.

2.3.1. CIRIA C683 The Rock Manual. 1) Jessen (1984) and Bradburyeral (1988) method

Through model test data of breast wall from studies by Jensen (1984) and Bradbury (1988), an empirical relationship has been fitted to test results for the structure configurations, shown in Figure 3.

\[ F_H = (\rho_w g d_{c1} L_{op}) \cdot (a H_s / R_{cs} - b) \]  

(6)

\[ F_u = (\rho_w g B_{c1} L_{op} / 2) \cdot (a H_s / R_{cs} - b) \]  

(7)
where, $\rho_w$ is the unit weight of sea water, kg/m$^3$. $H_S$ is the significant wave height, m. $L_{op}$ is the wavelength in deep water corresponding to the maximum period (the wavelength corresponding to $T_P$), m. $d_{ca}$ is the height of breast wall, m. $R_{ca}$ is the distance from the water level to the top of the armour block, m. The coefficients $a$ and $b$ are determined by looking up the table according to $H_S$, $L_{op}$ and $R_{ca}$. $B_c$ is the breast wall width, m. $F_H$ is the horizontal wave force imposed on the breast wall, kN. $F_u$ is the uplift wave force imposed on the breast wall, kN.

2) Pedersen method

Pedersen (1996) assumed that the magnitude of the impact pressure, $p_i$, can be determined as the stagnation pressure corresponding to the up-rush velocity at the edge of the armour crest. In other words, the water hits the wall face perpendicularly with a velocity equal to the up-rush velocity at the crest edge. The pressure distribution is shown in Figure 4 together with the hypothetical run-up wedge used for calculation.

\[ p_i = g \rho_w (R_{H, 0.1\%} - d_{ca}) \]
\[ y = \frac{(R_{H, 0.1\%} - d_{ca})}{\sin \alpha} \frac{(\sin 15^\circ)}{(\alpha - 15^\circ)} \]
\[ y_{eff} = \min\{y/2, d_{ca}\} \]
\[ F_{H, 0.1\%} = 0.21 \sqrt{L_{om}} \left(1.6p_iy_{eff} + Vp_{i}^2d_{c,prot}\right) \]
\[ M_{H, 0.1\%} = aF_{H, 0.1\%} = 0.55(d_{c,prot} + y_{eff})F_{H, 0.1\%} \]
\[ V_{p, 0.1\%} = 1.0Vp_i \]

where, $g \rho_w$ is the unit weight of the seawater, N/m$^3$. $R_{H, 0.1\%}$ is the 0.1 percent of wave run-up level, m. $d_{ca}$ is the vertical distance between SWL and the crest of armour berm, m. $\alpha$ is the angle between the protective surface and the horizontal water level, $^\circ$. $y_{eff}$ is the effective height in the impact zone, m. $d_{c,prot}$ is the distance from the top of the protective surface to the bottom of the breast wall, m. $Ba$ is the upper protective width of the upper slope of the breast wall, m. $L_{om}$ is the deep water wavelength corresponding to the mean wave period (wavelength corresponding to $T_m$), m. $F_H, 0.1\%$ is the total horizontal force with a 0.1 per cent probability of exceedance, N. $M_{H, 0.1\%}$ is the overturning moment, N • m. $p_{u, 0.1\%}$ is the uplift force, N/m$^2$. $pi$ is horizontal wave impact force component, N/m$^2$. And $V$ is a conversion factor less than 1, which is determined by wave run-up, block coverage height, and top surface width.

2.3.2. BS6349-7 “Guide for Design And Construction of Breakwater”

According to BS6349-7 “Guide for Design and Construction of Breakwater”, in the absence of physical model test data, the wave force for no broken wave can be estimated to be proportional to the difference between the significant wave height and the top height of the breast wall above SWL. It can be considered that the wave force $P_w$ (kN/m$^2$) is evenly distributed along the wall height, and its approximate value can be calculated by the following formula.

\[ P_w = KW_wL \left(\frac{H_S}{H_c} - 0.5\right) \]
where, $H_s$ is the significant wave height, m. $H_c$ is the top height of the breakwater, m. $L$ is the wavelength corresponding to the significant period, m. $W$ is the unit weight of water, kN/m³. $K$ is a dimensionless coefficient between 0.025 and 0.19, which can be taken as 0.25 for preliminary calculation.

Due to the lack of physical model test data, the wave force calculated according to different theories often differ greatly. Therefore, it is necessary to compare and analyze the calculation results under different methods of national codes, so as to provide theoretical support for the structure design.

3. Case study

3.1. Parameters

In this section, a revetment project in Africa is taken as an example to analyze the calculation results based on different national codes. The cross section of the revetment project is shown in Figure 5. The core is filled with 1 ~ 500kg of stones, on which there are 1180mm thick of 300 ~ 1000kg stones and 2460mm thick of 3t ~ 6t block stones. At the outer side is 5960mm thick of 48t artificial block stones. The top elevation of the cast-in-situ breast wall is +11.50m. Filter layers are set behind the core, in order to prevent the loss of backfill material. The seabed level is -14.2m.

The design water level is +1.78m, and the wave period $T_p$ is 17.39s. The average period $T_m$ is 13.58s, and the significant wave height $H_s$ is 8m. The deep water wavelength $L_{om}$ is 287.93m (corresponding to $T_p$).

3.2. Comparison of calculation results based on different methods in national codes

The wave force and wave moment on the breast wall are calculated according to Chinese, Japanese, and European codes. The calculation results are shown in Table 1 and Table 2, and the corresponding diagrams are shown in Figure 6 to Figure 10.

![Figure 5 Cross section of the revetment (level in m, dimension in mm)](image)

| Calculation results | Chinese Code | Japanese Code | The Rock Manual | BS6349-7 |
|---------------------|--------------|---------------|-----------------|----------|
|                      | not reduced | reduction factor = 0.7 | Code method | Jessen and Bradburyeral method | Pedersen method | K= 0.25 | K= 0.10 |
| $F_H$ (kN) | 1417 | 992 | 800 | 1122 | 994 | 2495 | 998 |
| $F_U$ (kN) | 1144 | 744 | 857 | 841 | 1112 | 1872 | 749 |
| $M_H$ (kN·m) | 7630 | 4959 | 3430 | 5608 | 5465 | 12477 | 4991 |
| $M_U$ (kN·m) | 11445 | 7439 | 8567 | 8411 | 11118 | 18716 | 7486 |
Table 2  Comparison of Calculation Results

| Item          | Deviation (%) |
|---------------|---------------|
|               |   |   |   |   |
| $F_h$ (kN)    | -19.3 | 13.1 | 0.2 | 151.6 | 0.6 |
| $F_u$ (kN)    | 15.1  | 13.1 | 49.5 | 151.6 | 0.6 |
| $M_h$ (kN·m)  | -30.8 | 13.1 | 10  | 151.6 | 0.6 |
| $M_u$ (kN·m)  | 15.1  | 13.1 | 49.5 | 151.6 | 0.6 |

It can be seen from Figure 6 to Figure 10 that the horizontal pressures imposed on breast wall are in rectangular distribution according to methods in Chinese code, BS6349 and the Jessen and Bradburyer method in the rock manual, while in trapezoidal distribution according to methods in Japanese code. In the Pedersen method, taking the top level of the protective blocks as the dividing line, the wave pressures below and above the dividing line are both in rectangular distribution, and the reduction is considered only in the lower rectangular. The uplift pressures is in triangular distribution in all diagrams.

By comparing the calculation results in Table 1 and Table 2, the following differences can be discussed and analyzed:

1. The horizontal wave force $F_h$ and its moment $M_h$ calculated by Japanese code are smaller than the corresponding values calculated by Chinese code considering a reduction factor of 0.7. The wave uplift force $F_u$ and moment $M_u$ calculated by Japanese code are larger than those calculated by Chinese code, mainly because the pressure at the bottom of breast wall calculated by Goda formula is larger.

2. The $F_{hi}$, $M_{hi}$, $F_u$ and $M_u$ calculated by Jessen and Bradburyer method are all 13.1% larger than the corresponding values calculated by Chinese code. This is mainly because the variable $L_{op}$ is calculated based on the largest wave period $T_P$. 
(3) The horizontal wave force $F_H$ calculated by Pedersen method is about 0.2% larger than the corresponding value calculated by the Chinese code, and the difference is quite small. The horizontal wave force moment $M_H$ is 10% larger than the corresponding value calculated by Chinese code, while the wave uplift force $F_u$ and moment $M_u$ is 49.5% larger than the corresponding value calculated by Chinese code. The differences can be analyzed by comparing code calculation results and graphic analysis. For code calculation, the value of the conversion coefficient $V$ of equation (13) in Pedersen method is taken as 1.0 in this project, and then $P_u$ is equal to $P_l$. The horizontal and vertical pressure at the bottom corner of breast wall are the same. From Figure 4, it can be seen that the corresponding wave pressure behind the covered block is reduced, and then $P_u$ are smaller than $P_l$. If the reduction is considered, $P_u$ can be reduced by 39%, and the calculated $F_u$ and $M_u$ based on the reduced $P_u$ are both about 8.5% smaller than those by Chinese code.

(4) $F_H$ and $M_H$, $F_u$ and $M_u$ calculated by BS6349 ($K = 0.1$) are all 0.6% larger than the corresponding values calculated by China code (reduction factor = 0.7), and the difference is quite small. It should be noted that the value range of $K$ is large, which has great influence on calculation results of wave force.

4. Conclusions
In this paper, different calculation methods for wave force based on the codes of China, Japan and Europe are discussed and analyzed. Besides, a revetment project in Africa is taken as an example to compare the calculation results. The conclusions can be obtained shown as follows.

(1) Reduction calculation of wave force is all considered in the Chinese, Japanese, and European codes. The reduction factor of 0.6-0.7 is adopted by considering the protection block or stone in front of breast wall in Chinese code. The overall reduction of wave force is considered through coefficient $\lambda_1$ and $\lambda_2$ in Japanese code. Reduction of wave force is considered through the coefficients $a$ and $b$ in Jessen and Braburyer method. Wave force reduction above the top surface of the amour block is not considered in Pedersen method while below the top surface is considered by introducing a conversion coefficient $V$. Dimensionless coefficient $K$ is placed as the reduction coefficient in BS6349.

(2) The wave force $F_H$, $M_H$, $F_u$ and $M_u$ calculated by Chinese code without considering reduction are relatively large. But by reduction calculation, the results are in the middle level, which are relatively reasonable.

(3) The Goda’s method in Japanese code is special for the calculation of wave force of vertical wall. When calculating the wave force imposed on breast wall placed on vertical wall, this method is practicable. As for the relevant calculation of the wave force imposed on breast wall on slope structures, it can only be used for approximate estimation. According to the comparison results, it turned out that the calculation value of wave force is relatively small, so this method is not recommended.

(4) When Jessen and Braburyer method is used to calculate wave force, the wave length corresponding to the maximum period ($T_p$) is used, and the calculated $F_H$, $M_H$, $F_u$ and $M_u$ are considerable large compared with other results. It is more appropriate of this method to be used for deep-water condition.

(5) In the Pedersen method, the effective height of the impact zone and wave force are both calculated through $R_u, 0.1%$. The calculation results of $F_H$ and $M_H$ are relatively reasonable, but $F_u$, $F_u$ and $M_u$ are relatively large, which can lead to conservative structure design.

(6) In the method of BS6349, the range of $K$ value is relatively large, which has great influence on the calculation results. When using this method, more attention should be paid to the selection of $K$ value.

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