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Research on Partial Coefficients for Design of Quarter-circular Caisson Breakwater

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Abstract: The quarter-circular caisson breakwater (QCB) is a new type of breakwater, and it can be applied in deepwater. The stability of QCB under wave force action can be enhanced, and the rubble mound engineering can be less than that of semi-circular breakwaters in deepwater. In order to study the wave force distribution acting on the QCB, to find wave force formula for this type of breakwater, firstly in this paper, the distribution characteristics of the horizontal force, the downward vertical force and the uplift force on the breakwater were gotten based on physical model wave flume experiments and on the analysis of the wave pressure experimental data. Based on a series of physical model tests acted by irregular waves, a kind of calculation method, which was modified by Goda formula, was proposed to carry out the wave force on the QCB. Secondly, the reliability method with correlated variables was adopted to analyze the QCB, considering the high correlation between wave forces or moments. Utilizing the observed wave data in engineering field, the reliability index and failure probability of QCB were obtained. Finally, a factor Q=0.9 is given to modify the zero pressure height above SWL of QCB, and wave force partial coefficient 1.34 to the design expressions of QCB for anti-sliding, as well as 1.67 for anti-overturning, were presented.

Keywords: quarter-circular caisson breakwater (QCB); wave force; modified Goda formula; reliability index; partial coefficient

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1 Introduction

Recent advances in the study of deepwater technology have led to the building and construction of large ports across various parts of the world. The invention of new types of breakwaters devices were developed, as well as its study and design. There are different cross sections of breakwater, such as caisson breakwater, composite breakwater, semi-circular breakwater and quarter-circular breakwater. The semi-circular breakwater was developed by the Port and Harbor Research Institute of Japan in the late of 1980s. The first experimental segment of semi-circular breakwater with 36 m length was built at Miyazaki harbor in Japan firstly.

Based on the semi-circular breakwater section, the quarter-circular caisson breakwater (QCB) was developed by China Communications First Design Institute of Navigation Engineering (Fig. 1). It was composed of quarter-circular crest, caisson and rubble mound. The structure is simple, possessing more stability and lower construction cost than other types of breakwater.

The calculation method of wave forces acting on the quarter- circular breakwater is considered an important study, and has been examined by port engineering investigators in previous research. The distribution characters of wave forces on the quarter-circular breakwaters were analyzed utilizing physical tests or theoretical research by researchers, as a result, wave calculation methods were respectively proposed.

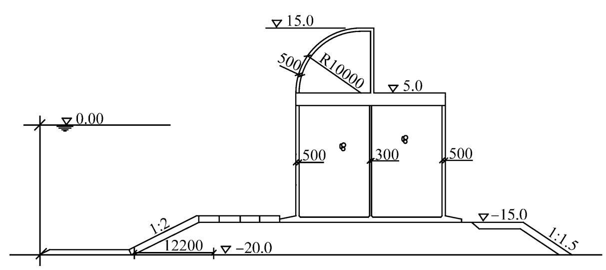

Fig. 1 Cross section of QCB

Based on the Goda formula for caisson breakwater, Tanimoto and Takahashi (1994) proposed a set of empirical formulas for calculating the wave force on semi-circular breakwater. Using irregular wave tests, Yu *et al*. (1999) studied the hydraulic character of semi-circular breakwaters, and a set of wave force formulas was given for semi-circular breakwaters, as well as that of submerged breakwaters. Yuan and Tao (2002, 2003) investigated the wave forces acting on the semi-circular breakwaters by a hybrid numerical method of boundary element method & finite difference, and a simple formula for calculating the wave forces on the breakwater was summarized. Li *et al*. (2003) discussed two sets of formulas under different conditions, and investigated the feasibility that consist of different parts of wave forces on semi-circular breakwaters, which were calculated by the formulas. Xie (1999) and Xie *et al*. (2006) researched the hydraulic characteristics of quarter-circular breakwaters, and proposed a simple calculation method of wave forces on quarter-circular

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breakwaters comparing with the test results between quarter-circular breakwaters and semi-circular ones. Jiang *et al*. (2008) simulated the hydraulic characteristics by numerical methods.

Combining the advantages of caisson breakwaters and that of quarter-circular breakwaters, QCB can be applied in deepwater with characters, such as simple section style, aesthetic, and lower cost. It is essential to calculate the wave forces acting on the QCB and to analyze the reliability of QCB. In this study, based on physical model tests, the statistic analysis of wave force distribution on QCB is carried out, and a set of wave force calculation formulas on QCB is proposed utilizing the Goda wave force formula on caisson breakwaters and that of the Japanese Port Research Institute on semi-circular breakwaters.

2 Physical model test of QCB

2.1 Model test design

Model experiments were carried out in the wave flume of Tianjin Port Engineering Institute, whose flume is 92-meter long, 4-meter wide and 1.8-meter height. Wave-making machine is an irregular wave maker, which is composed of hydraulic drive set, control system and computer. Both regular wave and irregular wave of different spectrum can be made by the system. The wave pressure data on QCB were recorded by data collection system utilizing wave height gauges, wave velocity meters and wave pressure sensors.

The QCB model was designed by gravity similarity criterion, and the model geometry scale was 1∶36. 25 wave pressure sensors were equally installed in the quarter crest, caisson wall and caisson slab of model, by which the wave pressure variation processes of 25 points can be synchronously recorded (Fig. 2).

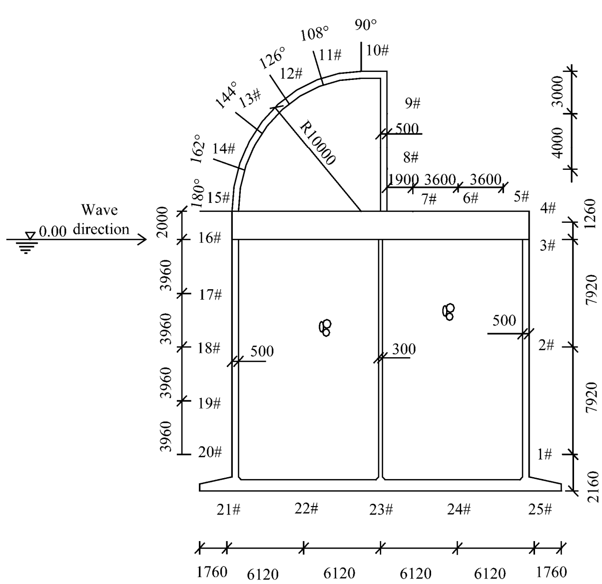

Fig. 2 Layout diagram of measurement points

Regular and irregular waves were adopted to act on the QCB. Besides the JONSWAP, the test wave spectrums include the wave spectrum of hydrology code for sea harbor of China.

The ratio of water depth in front of QCB and design wave height is: d/H=2.0–5.0; design wave height $H_{1\%}$ is 6–10 meters, average period T is 8–15 seconds. The wave parameters are listed in Table 1.

Table 1 Wave parameters of model test

Wave height $H_{1\%}$/m	Average period T/s
6.0	8, 9, 10
8.0	10, 11, 12
10.0	11, 13, 15

61 sets of irregular wave tests were designed for 7 cross sections in different cases (Table 2). The wave force history of every test point on QCB was recorded by a 0.02 seconds interval.

Table 2 Cross section dimensions of QCB m

Water depth	Bedding elevation	Seabed elevation	Circular elevation	Crest elevation	Caisson width
20.0	−15.0	−20.0	5.0	15.0	23.0
25.0	−18.0	−25.0	2.0	12.0	23.0
24.0	−11.0	−20.0	9.0	19.0	23.0
30.0	−18.0	−30.0	2.0	12.0	23.0
24.0	−8.0	−20.0	12.0	22.0	23.0
30.0	−15.0	−30.0.	5.0	15.0	23.0
34.0	−14.0	−30.0	6.0	16.0	23.0

2.2 Analysis of wave force experimental data

In this paper, the wave force distribution on the seaward side of QCB is investigated. Using the wave data statistical method, the action histories of the horizontal wave force, vertical downward force on the quarter-circular crest and the uplift force on the QCB are studied.

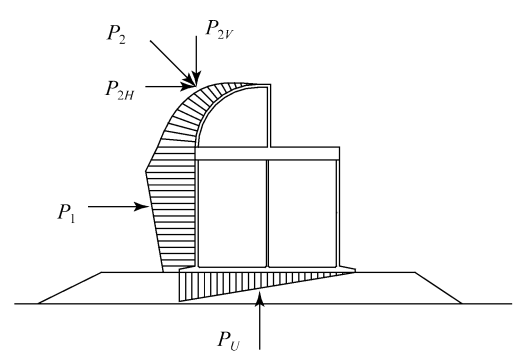

Fig. 3 Wave force distribution on QCB

The wave forces on the quarter-circular crest test points are decomposed into horizontal and vertical components, and the wave force P_{2H} and vertical force P_{2V} are integrated on the quarter-circular part. The total horizontal wave force P_H on QCB is composed of P_1 (wave force on caisson) and

P_{2H}, *i.e.* $P_H = P_1 + P_{2H}$. The downward vertical wave force on QCB is $P_V = P_{2V}$, and the uplift force on the caisson bed is P_U (Fig. 3).

The total horizontal wave force series P_H, downward force series P_V and uplift series P_U can be respectively carried out through 61 sets of wave force tests on QCB. By calculation procedures, the statistical characteristics of wave forces (P_H, P_V, P_U) on QCB are obtained for different cases, such as the time when P_H is at maximum value, wave pressures of test points reach their maximum values.

3 Wave forces on QCB

Since QCB is a new type of breakwater which takes advantage of caisson breakwater and semi-circular breakwater, the wave forces on the QCB can be calculated using the combined method of caisson breakwaters and semi-circular breakwaters.

3.1 Wave force acting on the caisson of QCB

When the wave acts on the breakwater, the wave forces on the caisson of QCB can be calculated using the Goda formula of caisson breakwater.

The wave pressure on still level water p_s (kPa) is:

$$p_s = 0.5(1+\cos\beta)(\alpha_1 + \alpha_2\cos^2\beta)\rho_0 H \tag{1}$$

The wave pressure at front toe of caisson p_b (kPa) is:

$$p_b = \alpha_3 p_s \tag{2}$$

Wave pressure at sea bed p_d (kPa) is:

$$p_d = \frac{p_s}{\cosh kd} \tag{3}$$

The wave pressure on the slab seaward is p_u (kPa):

$$p_u = 0.5(1+\cos\beta)\alpha_1\alpha_3\rho_0 H \tag{4}$$

And p_a (kPa), which is the wave pressure at the intersection of caisson and crest, can be gotten utilizing linear interpolation by p_s, p_d and the zero pressure point. In which

$$\alpha_1 = 0.6 + 0.5\left[\frac{4\pi d/L}{\sinh(4\pi d/L)}\right]^2$$

$$\alpha_2 = \min\left\{\frac{H'-d}{3H'}\left(\frac{H}{d}\right)^2, \frac{2d}{H}\right\}$$

$$\alpha_3 = 1 - \frac{d_1}{d}\left[1 - \frac{1}{\cosh(2\pi d/L)}\right]$$

where H is the design wave height (m), L the wave length (m), d the water depth in front of breakwater (m), and ρ_0 the density of water (kN/m^3). And $k=2\pi/L$, d_1 is the water depth above bedding (m), H' is the water depth 5 times of H_S (effective wave height) away from the breakwater, β denotes the angle between wave direction and the normal direction of breakwater axes (º).

3.2 Wave forces acting on the quarter-circular crest of QCB

As the wave was approached, it is advised to calculate the wave forces acting on the quarter-circular crest of QCB by using the Goda formula on semi-circular breakwater which was recommended by Japan harbor Institute.

The zero pressure height above still water level (SWL) is:

$$\eta = 0.75(1+\cos\beta)H \tag{5}$$

With the phase difference between the vertical and the quarter-circular breakwaters, the wave pressure at the bottom of crest point p_a (kPa, based on the Goda fomula) on QCB should be modified:

$$p'_a = \lambda_p p_a \tag{6}$$

where λ_p is the correction factor for phase, and Δl is the horizontal distance between action points p_a' and p_S'.

$$\lambda_p = \cos^4\left(\frac{2\pi\Delta l}{L}\right)$$

The modified wave pressure is expressed as $p'(Z)$, where Z indicates the height from the bottom of quarter-circular curve. The wave pressure acting on the normal direction of quarter-circular curve is expressed as:

$$p(\theta) = p'(Z)\cos(\theta) \tag{7}$$

where θ denotes the central angle.

The distribution of uplift force on the QCB is the same as that on the caisson breakwater.

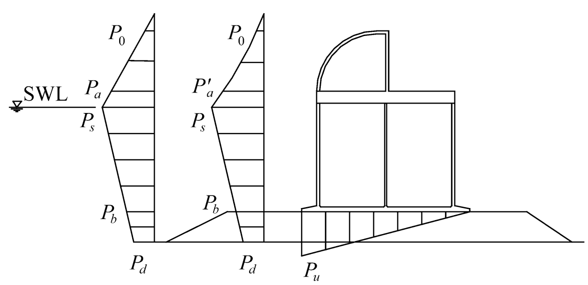

Fig. 4 The wave force distribution on QCB

3.3 Comparison of test wave force and calculation result

In order to compare the results between the test wave force and the calculation result using proposed formula in above section, an uncertainty factor is defined as: $\alpha = P_t / P_c$, where P_t denotes the wave force using test pressures on QCB, P_c is the calculating wave force by proposed formula.

For the case of $H_{1\%}$=6.0 m, the wave force distribution on QCB is similar to that of caisson breakwater, so the rest 34-set large wave height conditions are taken into account. Utilizing the test wave pressures for the different cases, the uncertainty factors of wave forces on QCB would be calculated, as well as the statistics of uncertainty factors.

Through the analyzing of uncertainty factors, the test force P_H and P_U are close to the calculated ones for most cases. Since the test values P_V is smaller than the calculated values, and the wave force P_V turns of to be an advantage for the stability of QCB, the larger P_V achieved by the formula will be an disadvantageous, therefore, the formula for calculating vertical downward force on quarter-circular of QCB will need modifications(Fig. 5, Table 3).

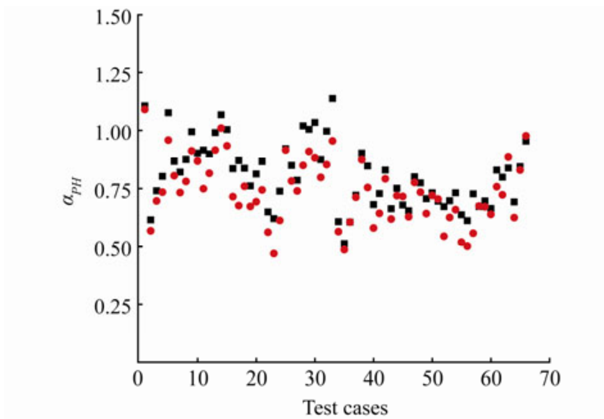

Fig. 5 Uncertainty factors of wave force P_H on QCB

Table 3 Statistics of uncertainty factors

Item	Uncertainty factor	Mean	Standard deviation
P_H reached its maximum value	α_{PH}	0.886 5	0.132 6
	α_{PV}	0.643 4	0.273 6
	α_{PU}	0.805 6	0.197 4
P_U reached its maximum value	α_{PH}	0.792 3	0.134 5
	α_{PV}	0.338 2	0.176 1
	α_{PU}	0.912 2	0.176 1
P_H reached its 1% maximum value	α_{PH}	0.725 1	0.092 7
	α_{PV}	0.502 4	0.187 7
	α_{PU}	0.684 7	0.152 0
P_U reached its 1% maximum value	α_{PH}	0.680 4	0.111 9
	α_{PV}	0.374 8	0.197 3
	α_{PU}	0.729 3	0.128 8

For different cases, the uncertainty factor statistics of α of horizontal wave force P_{2H} above SWL, as well as uncertainty factor ε of η, are listed in Table 4.

Table 4 Uncertainty factor statistics of α and ε

Uncertainty factors	Cases	mean	Standard deviation
α	Max(P_{2H})	0.723 3	0.168 5
	1% max(P_{2H})	0.596 7	0.112 0
	Max(P_U)	0.482 4	0.134 4
	1% max(P_U)	0.478 7	0.136 2
	Max pressures	0.859 4	0.140 6
	1% max pressures	0.624 1	0.110 8
ε	Max pressures	0.906 9	0.100 7
	1% max pressures	0.902 9	0.104 6

Table 4 shows that the means of uncertainty factors (α and ε) are close to 0.9 for the worst case, in which the wave pressures of all test points have reached their maximum values. The height (η) of zero pressure point above SWL is an important factor that has influenced P_V, it is necessary to correct the height formula of Eq. (5).

4 The proposed formula for wave force calculation of QCB

Through the above researches of wave force distribution on QCB, a modified Goda formula is proposed to calculate the wave forces on the QCB in this paper, a modifying factor Q is used to reduce η in Eq. (5). Based on the results in Table 4, the mean of ε is in the range of 0.906 9 to 0.902 9, the proposed value of Q is taken as 0.90.

A new method for calculating the wave force on QCB is devised based on utilizing the combined Goda formula. The water height above SWL (m) is:

$$\eta' = Q \cdot \eta = 0.675\left(1+\cos\beta\right)H \tag{8}$$

Especially, when the angle $\beta = 0$, the η value of QCB would be simplified as $\eta = 1.35H$.

The wave pressure at SWL is p_s' (kPa):

$$p_s' = p_s \tag{9}$$

The wave pressure at caisson toe is p_b' (kPa):

$$p_b' = p_b \tag{10}$$

The wave pressure at sea bed is p_d' (kPa):

$$p_d' = p_d \tag{11}$$

The wave pressure at sea side of caisson slab is p_u' (kPa):

$$p_u' = p_u \tag{12}$$

The wave pressure at the joint point of caisson and quarter-circular crest is p_a (kPa) (after phase correction):

$$p_a'' = p_a' \tag{13}$$

The wave pressure at the quarter-circular crest is controlled by $p(\theta)$ (kPa):

$$p'(\theta) = p(\theta) \tag{14}$$

5 Reliability analysis of QCB

5.1 Wave parameters in engineering field

The wave parameters in engineering field from 1988 to 2007 are investigated, which include the annual extreme statistics of wave height and average period in 5 directions. The wave heights and periods in E-ESE direction are relatively larger than other directions. Therefore, the annual extreme values in E-ESE directions are used to analyze the stability of QCB (Fig. 6, Fig. 7). Utilizing the analysis of wave parameters in E-ESE direction by Pearson-III curves, the wave height and the period once in 50-year can be carried out, which are $H_{1\%} = 7.70$ m and $T = 10.67$ s (Fig. 8, Fig. 9).

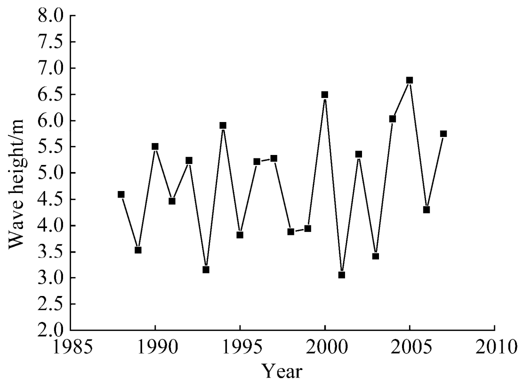

Fig. 6 Annual extreme values of wave height ($H_{1\%}$)

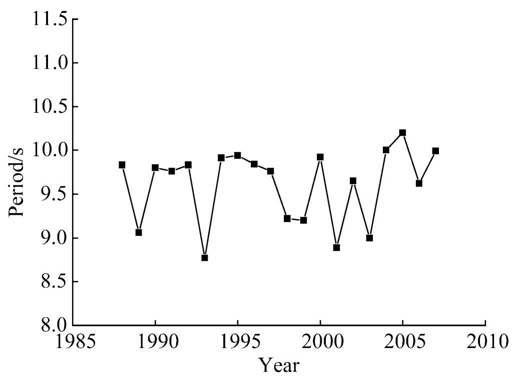

Fig. 7 Annual average value of wave period (T)

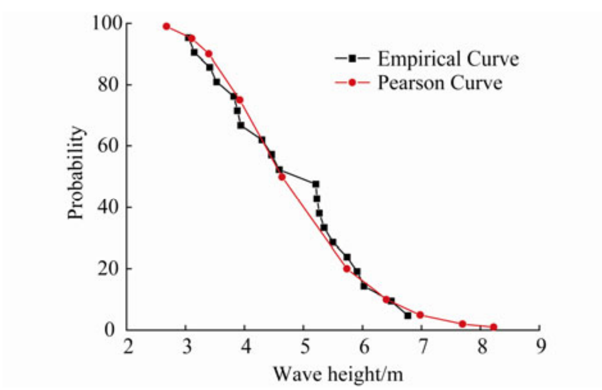

Fig. 8 Cumulative frequency curves of wave height

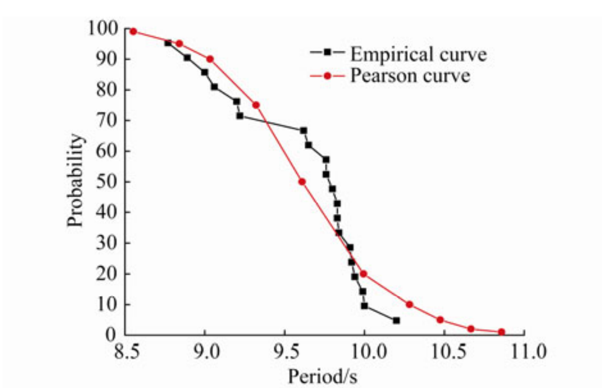

Fig. 9 Cumulative frequency curves of wave period

Liu (1993) researched the observed wave data in China, and found that the long-term probability distribution of wave action followed the log-normal or Gumbel distribution. After Kolmogorov-Smirnov testing (K-S Test), Qie and Li (2004), Qie and Choi (2010) pointed out that the long-term distribution of characteristic wave force met the Gumbel distribution. In this study, the Gumbel distribution is adopted as wave probability distribution.

5.2 Design cross section dimensions of QCB

12 cross sections in different cases are presented in Table 5.

Table 5 Cross section dimensions of QCB m

Water depth	Bedding elevation	Seabed elevation	Crest point	Top elevation	Caisson width
20.0	−15.0	−20.0	5.0	15.0	21.0
20.0	−15.0	−20.0	5.0	15.0	23.0
25.0	−18.0	−25.0	2.0	12.0	21.0
25.0	−18.0	−25.0	2.0	12.0	23.0
24.0	−11.0	−20.0	9.0	19.0	21.0
24.0	−11.0	−20.0	9.0	19.0	23.0
30.0	−18.0	−30.0	2.0	12.0	21.0
30.0	−18.0	−30.0	2.0	12.0	23.0
30.0	−15.0	−30.0	5.0	15.0	21.0
30.0	−15.0	−30.0	5.0	15.0	23.0
34.0	−14.0	−30.0	6.0	16.0	21.0
34.0	−14.0	−30.0	6.0	16.0	23.0

5.3 Characteristics of wave forces on QCB

Based on the modified Goda formula in last section, the series of P_H, P_U, P_V are calculated by 20-year statistic wave actions (Fig. 10).

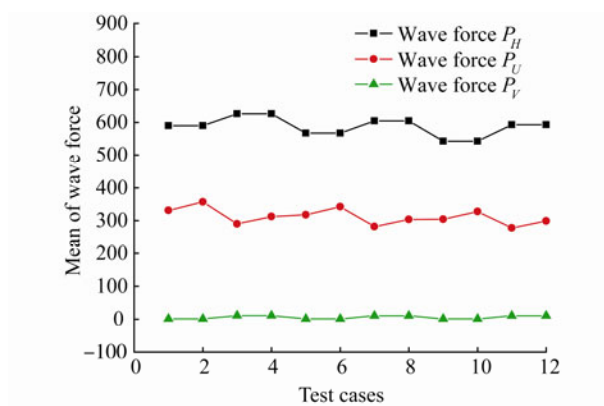

Fig. 10 Mean values of wave forces on QCB

The climb height of wave on the quarter-circular crest is influenced by the water depth in front of breakwater and the location of circular crest, as well as the wave parameters, therefore, the vertical force on the crest part is different in the above 12 cases. Since the correlative coefficients between wave forces, as well as wave moments, are close to 1.0, the correlative influence is taken into account in the reliability analysis of QCB.

Utilizing the exceeded 1% wave height once in 50-year, $H_{1\%}$= 7.70 m, and average period T = 10.67 s, the standard values of wave loadings are gotten by modified Goda formula.

Table 6 Standard values of wave loadings on QCB

P_{HK} /kN	P_{UK} /kN	P_{VK} /kN	M_{HK} /kNm	M_{UK} /kNm	M_{VK} /kNm
1 150.93	599.57	16.45	12 485.75	8 893.59	337.84
1 150.93	645.69	16.45	12 485.75	10 438.64	370.74
1 210.97	531.89	64.01	15 177.63	7 889.70	1 263.60
1 210.97	572.80	64.01	15 177.63	9 260.34	1 391.62
1 113.18	572.96	15.88	12 064.97	8 498.89	326.19
1 113.18	617.03	15.88	12 064.97	9 975.36	357.96
1 167.48	510.22	61.53	14 610.05	7 568.31	1 214.63
1 167.48	549.47	61.53	14 610.05	8 883.12	1 337.69
1 067.38	542.95	15.19	11 551.51	8 053.75	311.92
1 067.38	584.71	15.19	11 551.51	9 452.89	342.29
1 140.79	497.60	59.98	14 257.67	7 381.03	1 183.92
1 140.79	535.87	59.98	14 257.67	8 663.30	1 303.87

5.4 Reliability analysis of QCB

In this case study, the reliability analyses of the QCB are limited in cases of anti-sliding and anti-overturning. The safety factor for sliding is

$$K_S = \left(W - P_U + P_V\right) \cdot f / P_H \tag{15}$$

In which P_H, P_U and P_V indicate the horizontal wave force, the uplift on the structure, and the vertical downward force on quarter-circular part, respectively. The term, f, denotes the friction factor between breakwater and foundation, which has a probability distribution that is normal with m_f=0.6 and σ_f= 0.026 (Liu and Xie, 1993). The weight of QCB in water, W, is regarded as a constant.

The design expression for sliding is

$$\left(\frac{1}{\gamma_R} W - \gamma_{PU} P_U + \gamma_{PV} P_V\right) \cdot f \geq \gamma_{PH} P_H \tag{16}$$

where γ_R denotes the resistant partial coefficient of weight, and γ_{PH}, γ_{PU}, and γ_{PV} respectively denote the partial coefficients of P_H, P_U, and P_V in case of sliding.

The safety factor against overturning is

$$K_O = (M_W + M_V) / \left(M_H + M_U\right) \tag{17}$$

In which M_H, M_U, and M_V respectively indicate the horizontal wave force moments, the uplift moment on the structure, and the vertical downward force moment on quarter-circular part, which follow a Gumbel distribution. The weight moment of QCB in water, M_W, is regarded as a constant.

The design expression for overturning is

$$\frac{1}{\gamma_R} M_W \geq (\gamma_{MU} M_U - \gamma_{MV} M_V + \gamma_{MH} M_H) \tag{18}$$

In which, γ_R indicates the resistant partial coefficient of weight moment, γ_{MH}, γ_{MU} and γ_{MV} respectively indicate the partial coefficients of M_H, M_U, and M_V in case of overturning.

Based on the reliability index β, results of the QCB for anti-sliding and overturning in different cases by Hasofer-Lind method, Fig. 11 to Fig. 16 show the relation fitting curves of the safety factor K and reliability index β, as well as the reliability index, β, partial coefficients, and failure probabilities P_f.

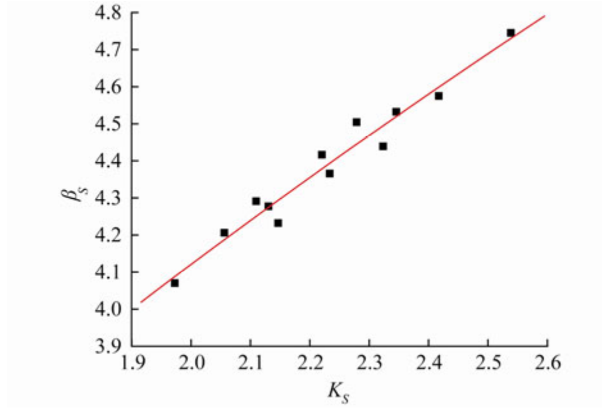

Fig. 11 Fitting curve of K_S versus β_S

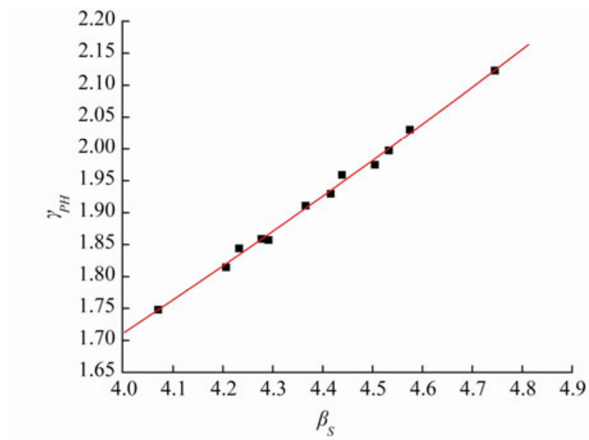

Fig. 12 Fitting curve of β_S versus γ_{PH}

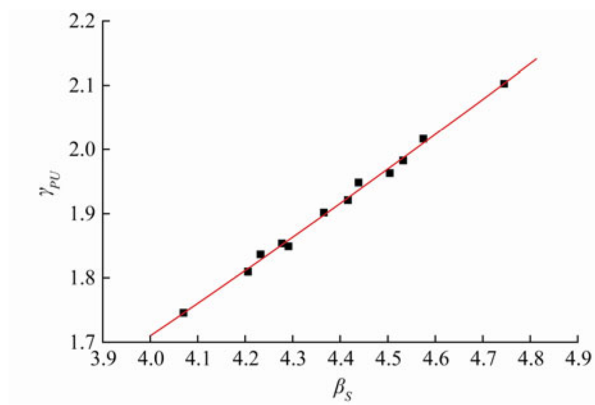

Fig. 13 Fitting curve of β_S versus γ_{PU}

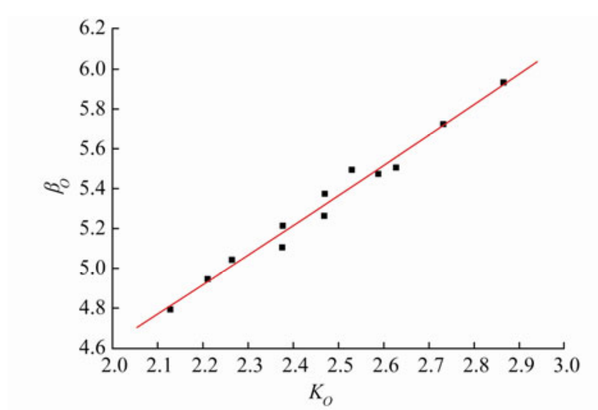

Fig. 14 Fitting curve of K_O versus β_O

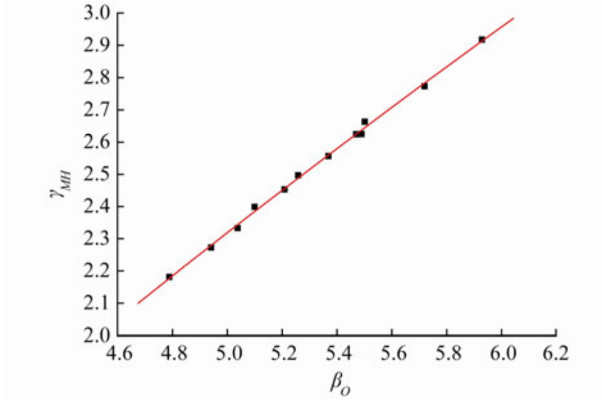

Fig. 15 Fitting curve of β_O versus γ_{MH}

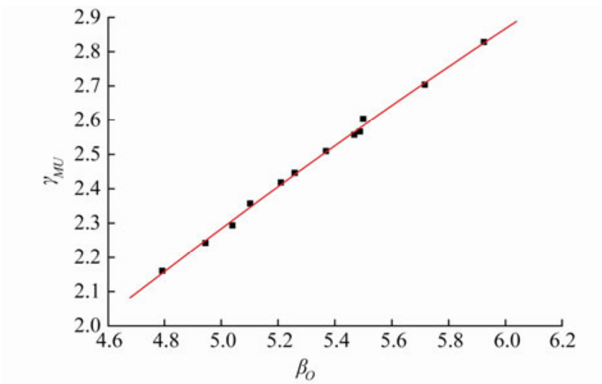

Fig. 16 Fitting curve of β_O versus γ_{MU}

For the study cases, the partial coefficients of wave action on QCB are proposed:

1) The resistant coefficients of weight and its moment are taken as 1.0, γ_R =1.0.

2) Because the vertical wave force P_V (as well as its moment M_V) is advantageous in stability of QCB, the partial coefficients γ_{PV} and γ_{MV} are taken as 1.0, *i.e.* γ_{PV}=1.0, γ_{MV}=1.0.

3) When K_S =1.30 is taken for the case of anti-sliding, the corresponding index and coefficients are β_S=3.223 6, γ_{PH}=1.338 8, γ_{PU} =1.341 3. The failure probability of structure is P_f=6.329 5×10^{-4}.

4) For the case of anti-overturning, if K_O =1.60, the corresponding index and coefficients are β_O =4.048 3, γ_{MH}=1.662 7, γ_{MU} =1.670 3, and P_f=2.570 7×10^{-5}.

6 Conclusions

The quarter-circular caisson breakwater is a new type of breakwater in used in the study of deepwater. Utilizing a series of physical model tests acted by irregular waves, a simplified calculation method for wave force, which is modified from Goda formula, is proposed to execute the wave force on the QCB. A factor Q=0.9 is provided to modify the zero pressure height above SWL of QCB.

Based on the observed wave data in engineering field, the reliability index and failure probability of QCB are achieved, as well as the proposed partial coefficients of wave loadings.
And the design expressions of QCB in deep water are proposed as follows.

In case of anti-sliding:

$$(W+P_V)\cdot f \geq 1.34(P_H+P_U\cdot f) \tag{19}$$

In case of anti-overturning:

$$(M_W+M_V) \geq 1.67(M_H+M_U) \tag{20}$$

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