Transformation of statistical and spectral wave periods crossing a smooth low-crested structure

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Smooth emerged breakwater

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Abstract

We carried out experimental studies of a smooth submerged breakwater in a wave channel in order to study such a structure impacts on the changes of statistically and spectrally defined representative wave periods as waves cross it. We discuss the impact of relative submersion, i.e. the relationship between the breakwater crown submersion and the incoming significant wave length R_c/L_{s-i}, on the representative wave periods. The mean periods, estimated using statistical and spectral methods, were compared in front of and behind the breakwater: the two periods turned out to be identical. Based on the measurements of the spectral mean wave periods in front of and behind the breakwater, an empirical model is derived for estimating the reduction in mean spectral period for submerged and emerged smooth breakwaters.

The complete text of the paper is available at http://www.iopan.gda.pl/oceanologia/

1. Introduction

It is usual to use the characteristic periods and heights of incoming irregular waves for calculating run up, overtopping, morphological changes and reflection from perforated seawalls. If a coastal structure is defended by a smooth submerged breakwater, it is important to calculate the modified wave parameters behind it.

When waves cross a breakwater, wave breaking and nonlinear interactions occur between the components of wave spectra. These interactions cause a transition of wave energy from primary harmonics to higher harmonics of the wave spectra. The amount of energy transferred depends on the incoming wave parameters, breakwater geometry and water depth. Beji & Battjes (1993) observed high frequency wave energy amplifications as waves propagate over a submerged bar in a laboratory experiment. They found that the bound harmonics were amplified during shoaling and released in the deeper water region after the bar crest. Wave breaking itself is a secondary effect in this process, dissipating the overall wave energy without significantly changing its relative spectral distribution.

Generally speaking, knowledge of the impact of breakwater geometry and incoming wave parameters on wave spectrum deformation is insufficient. The transfer of energy to higher harmonics of the wave spectra leads to a transformation in statistical and spectral wave periods. The present study addresses the problem of the impact of breakwater geometry and incident wave parameters on wave period transformation. Breakwater geometry refers to the submersion of the breakwater crown, the wave parameters to wave height and length.

The general conclusion of the works of Goda et al. (1974), Tanimoto et al. (1987) and Raichlen et al. (1992) is that when waves cross a low-crowned breakwater, mean spectral wave periods are reduced by 60% in relation to incoming mean wave periods. Van der Meer et al. (2000) conducted tests on smooth emerged breakwaters and found that the transmitted mean spectral wave period was reduced by up to 40% compared to the incident one. They also concluded that the mean and peak wave periods were reduced by the increase in the wave height transmission coefficients. Briganti et al. (2003) studied the impact of wave height transmission coefficients on the transfer of energy from lower to higher harmonics. They established that the deformation of the wave spectra when waves cross breakwaters differs for low crested structures with smooth surfaces and with rubble mound armour. Wang et al. (2007) studied the impact of the angle of incoming waves on the transformation of the mean spectral centroid period. Tests were conducted for breakwaters with submerged and emerged crowns, as well as with the crown level with the water surface. It was established that in the case of approximately normal incident waves approaching the breakwater, the mean centroid periods were reduced by up to 25% in relation to the incoming period.

2. Material and methods

Laboratory tests were conducted with a piston wave generator using the AWACS system (anti-reflecting system). A dissipation chamber was situated at the end of the channel, which gives a maximum reflection coefficient 0.2 for the longest wavelengths cited in Table 1 in the empty

Table 1. Wave parameters used in laboratory testing and results of measurements of transmitted wave parameters, standard JONSWAP spectrum ($g = 3.3$, $s_1 = 0.07$, $s_2 = 0.09$), K_r – measured reflection coefficient from the submerged breakwater

$R_{c_2} = -0.055$ m							
	measured incident			measured transmitted			
Test	$H_{m_{0-i}}$ [m]	$T_{0.2-i}$ [s]	T_{p-i} [s]	$H_{m_{0-t}}$ [m]	$T_{0.2-t}$ [s]	T_{p-t} [s]	K_r [1]
1	0.060	0.66	0.68	0.040	0.65	0.80	0.34
2	0.058	0.72	0.81	0.041	0.65	0.80	0.31
3	0.055	0.85	1.01	0.041	0.69	0.98	0.25
4	0.099	0.81	0.89	0.051	0.73	0.91	0.27
5	0.096	0.92	1.10	0.055	0.77	1.07	0.23
6	0.089	1.15	1.45	0.058	0.85	1.42	0.26
7	0.121	0.89	0.99	0.058	0.79	0.98	0.26
8	0.113	1.01	1.24	0.062	0.82	1.16	0.25
9	0.104	1.32	1.68	0.066	0.95	1.71	0.32

$R_{c_1} = -0.10$ m							
	measured incident			measured transmitted			
Test	$H_{m_{0-i}}$ [m]	$T_{0.2-i}$ [s]	T_{p-i} [s]	$H_{m_{0-t}}$ [m]	$T_{0.2-t}$ [s]	T_{p-t} [s]	K_r [1]
10	0.062	0.66	0.68	0.053	0.69	0.80	0.36
11	0.065	0.72	0.81	0.055	0.72	0.85	0.33
12	0.064	0.85	1.01	0.057	0.80	0.98	0.26
13	0.103	0.81	0.89	0.076	0.80	0.98	0.28
14	0.105	0.92	1.10	0.081	0.85	1.07	0.23
15	0.106	1.15	1.45	0.084	0.93	1.42	0.26
16	0.126	0.89	0.99	0.087	0.85	0.98	0.24
17	0.127	1.01	1.24	0.091	0.89	1.28	0.23
18	0.126	1.32	1.68	0.094	1.01	1.71	0.31

channel (without a breakwater). The wave channel width was 1 m, the height 1.1 m, and the depths of water in the channel were $d_1 = 0.44$ m and $d_2 = 0.4$ m. The submerged breakwater model was made of wood, the crest width being $B = 0.16$ m and the slope 1:2 (Figure 1). The measurements were performed for two submersions of the wave crown ($R_{c_1} = -0.055$ m and $R_{c_2} = -0.101$ m), achieved by changing the depths of water in the channel to $d_1 = 0.4$ m and $d_2 = 0.446$ m. Measurements were performed in conformity with Table 1 for each depth, yielding a total of 18 measurements. The duration of an experiment was ~ 5 min., which is equivalent to approx. three hundred waves per experiment, according to the recommendations by Journée & Massie (2001).

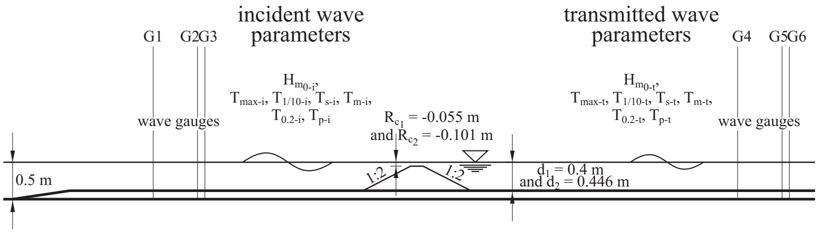


Figure 1. Details of the wave flume and measured incident and transmitted wave parameters

Capacitive gauges G1–G6 were used for measuring surface elevation. The measured data were processed according to spectral and statistical (zero up-crossing) methods. According to the spectral principle, the spectral wave parameters were established as H_{m_0}, $T_{0.2}$ and T_p (see the list of symbols at the end of the paper). The incident wave parameters were determined by separating the incoming and reflected spectra on gauges G1–G3, and the transmitted wave parameters by separation on gauges G4–G6. The Zelt & Skjelbreia (1992) method was used for separating the incident spectrum from the reflected one.

The statistical wave parameters H_{max}, $H_{1/10}$, H_s, H_m, T_{max}, $T_{1/10}$, T_s and T_m were defined by zero up-crossing for incident and transmitted wave time series (see list of symbols). Incident and transmitted wave time series were determined by inverting FFT of the incident and transmitted spectrum defined by the procedure described in the previous paragraph. To avoid the influence of wave reflection from the breakwater and dissipation chamber, the positions of the gauges were chosen to be a minimum of one wavelength away from the structure, thereby preventing spatial variation of the statistical parameters (Goda 2000).

3. Results and discussion

3.1. Reduction in wave periods as a result of wave transmission over a breakwater

The process of non-linear interaction can be explained from the point of view of physics in the following way: when a longer wave from an irregular wave train crosses the breakwater, waves of shorter periods are superimposed on its wave profile, thereby reducing the statistical wave train periods. The phenomenon is evident in waves of considerable length but is less noticeable in shorter waves. Figure 2 presents an example of a time series (for Test 8, Table 1) with a considerable incident mean wave period T_m. This is an evident occurrence of superimposed shorter waves, which generate a larger number of waves behind the breakwater (calculated by the zero up-crossing method).

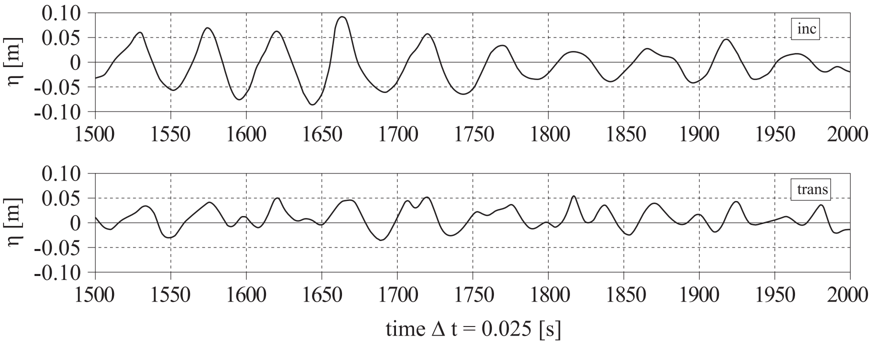


Figure 2. Incident and transmitted wave time series for raw data recorded on gauge G1 (inc) and gauge G4 (trans), (Test 8, Table 1)

Figure 3 shows an example of a time series (for Test 2, Table 1) with a shorter incident mean period T_m. There is no significant occurrence of superimposed shorter waves.

The phenomenon is therefore more pronounced in wave trains with a smaller R_c/L_{s-i} ratio. The reduction in the statistical wave periods ($T_{1/10-t}$, T_{s-t} and T_{m-t}) of the wave train, behind the breakwater, thus depends on the relative submersion R_c/L_{s-i} (Figure 4).

The greatest reduction occurs at T_m, because it covers all the waves from the record, including the newly formed short period waves. Significantly, T_s and one tenth $T_{1/10}$ wave periods indicate a smaller reduction in relation to the reduction of the mean period. The maximum period is related to the wave of the greatest wave height in the wave train. As this value is not subject to statistical averaging, it causes extreme oscillations of relations T_{max-t}/T_{max-i}, and only limited conclusions can be drawn.

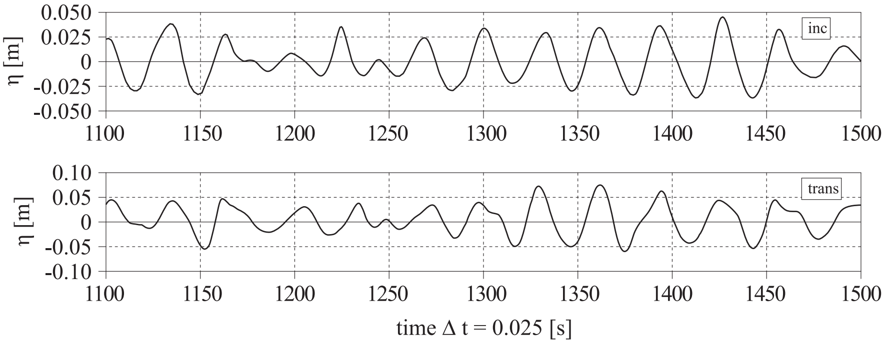


Figure 3. Incident and transmitted wave time series for raw data recorded on gauge G1 (inc) and gauge G4 (trans), (Test 2, Table 1)

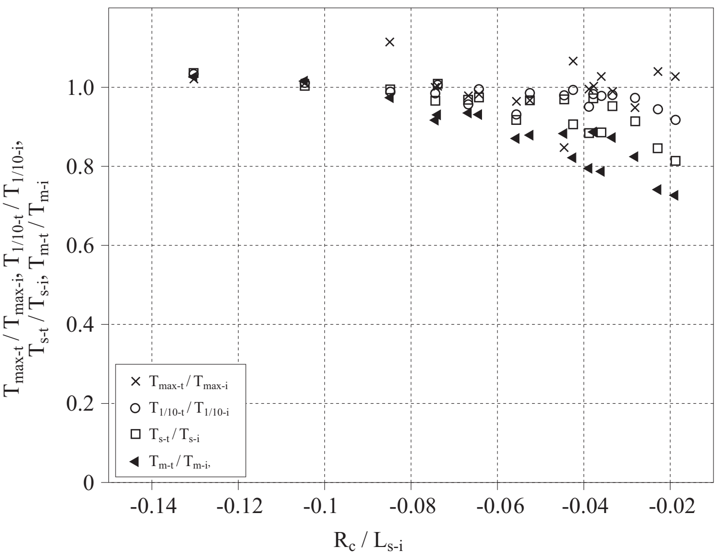
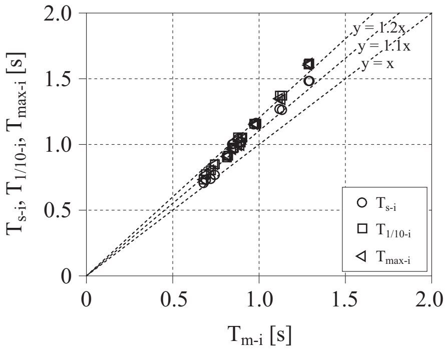


Figure 4. Reduction in statistical wave periods crossing a smooth submerged breakwater; T_{max-i}, $T_{1/10-i}$, T_{s-i}, T_{m-i} – incident wave periods; T_{max-t}, $T_{1/10-t}$, T_{s-t}, T_{m-t} – transmitted wave periods

In general, representative statistical wave periods are correlated, whereas the empirical interrelations were defined by Goda (1974, 2008) as $T_{max} \approx T_{1/10} \approx T_s \approx 1.1$–$1.2\ T_m$. Considering that statistical periods depend on the form of the wave spectrum (Goda 2008), and that deformations of the wave spectrum occur when waves cross the breakwater, the question arises in what way the above relations between statistically representative periods change when the waves cross the breakwater. Figure 5-left shows



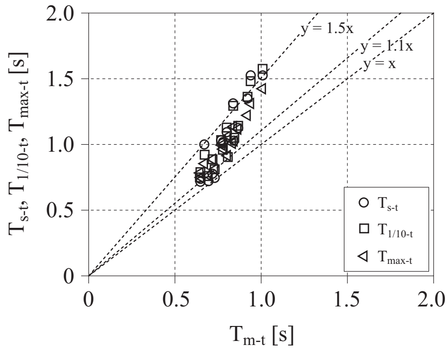


Figure 5. Ratio of statistical wave periods T_{max-i}, $T_{1/10-i}$ and T_{s-i} in front of (left) and T_{max-t}, $T_{1/10-t}$ and T_{s-t} behind (right) a smooth submerged breakwater with mean statistical periods T_{m-i} and T_{m-t} (ordinate-y, abscissa-x)

the relations between the statistical periods T_{max}, $T_{1/10}$ and T_s and the mean period T_m in front of the breakwater. All the values are positioned between lines $y = 1.1\,x$ and $y = 1.2\,x$, which corresponds approximately to the above empirical interrelations. Figure 5-right illustrates the relations of the same statistical parameters behind the breakwater. There is a change in these relations when in higher periods the relationship tends to $T_{max} \approx T_{1/10} \approx T_s \approx 1.5\ T_m$. This happens because when the waves cross the breakwater, a more significant reduction in the mean period T_m occurs (Figure 4) in relation to the other periods T_{max}, $T_{1/10}$ and T_s. T_m is more significantly reduced by the appearance of high frequency harmonics (short waves), which are not so important from the engineering point of view because of their small height. So one should be careful when applying the mean period T_m to engineering purposes in the case of submerged structures.

As a consequence of wave spectrum deformation, i.e. wave nonlinearity effects in shallow water, an error could occur when estimating the mean spectral period, $T_{0.2}$ (see list of symbols), which may be underestimated by as much as 70% of the statistical mean period T_m (Longuet-Higgins 1983). Since wave spectra are deformed when waves cross a breakwater, the question arises whether a similar mistake might be expected in the estimation of the transmitted mean spectral period $T_{0.2-t}$.

Figure 6 illustrates the ratio of mean statistical and spectral wave periods for incident and transmitted waves: mean spectral $T_{0.2-i}$ is compared with T_{m-i} for incident waves, and $T_{0.2-t}$ is compared with T_{m-t} for transmitted waves.

It can be concluded that wave spectra deformation does not influence the calculation accuracy of spectral mean periods $T_{0.2-t}$.

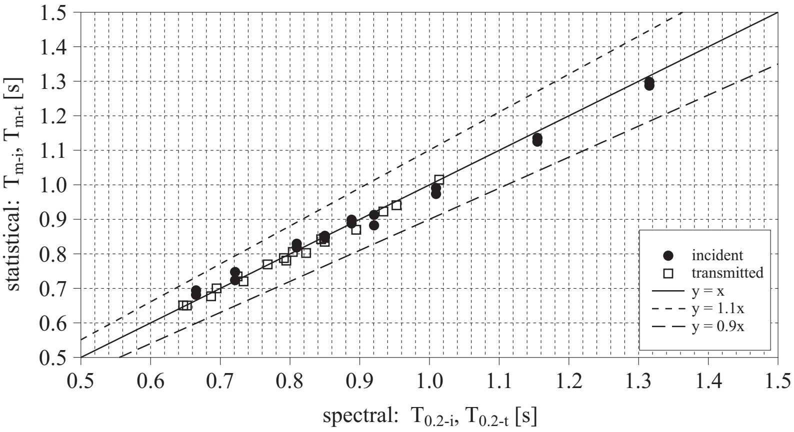


Figure 6. Ratio of spectral ($T_{0.2}$) and statistical (T_m) mean wave periods for incident and transmitted waves at a smooth submerged breakwater

It has already been mentioned that in the process of wave transmission over a breakwater, the wave energy is transmitted to higher frequencies, along with the increase in the term m_2 (second moment), resulting in a reduction in the mean spectral wave period of transmitted waves $T_{0.2}=\sqrt{m_0/m_2}$ and the reduction of the $T_{0.2-t}/T_{0.2-i}$ ratios in the function of relative submersion $R_c/L_{0.2-i}$ (Figure 7). The data from Van der Meer et al.

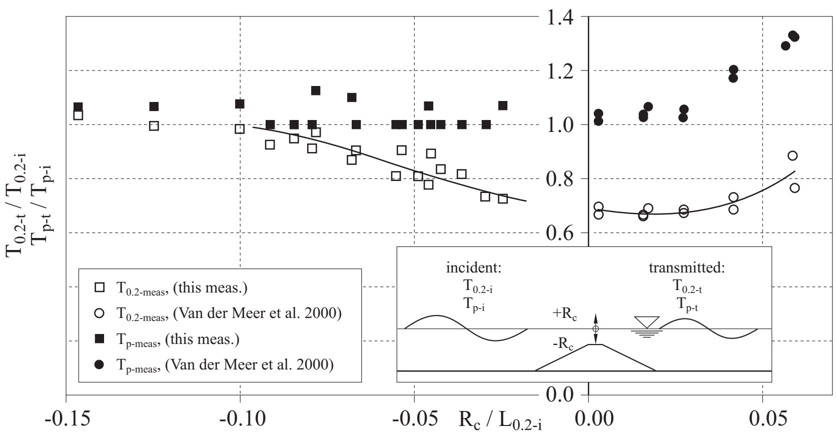


Figure 7. Dependence of parameters $T_{0.2-t}/T_{0.2-i}$ and T_{p-t}/T_{p-i} on relative submersion $R_c/L_{0.2-i}$, for a smooth breakwater with submerged crown (from this paper) and an emerged crown as per Van der Meer's (Van der Meer et al. 2000) measurements with crown width $B_b = 0.13$ and 0.3 m; $H_{m_0} = 0.09$–0.14 m, wave steepness $s_{op} = 0.03$, water depth $d = 0.29$–0.37 m, breakwater slope 1:4, $R_c/H_{m_0} = 0$–1.0

(2000) for smooth emerged breakwaters with a similar breakwater geometry and similar wave parameters as in this paper are used for comparison. In such a way, the reduction of the mean spectral wave periods $T_{0.2}$ for a wider range of relative submersion $R_c/L_{0.2-i}$, namely from -0.15 to -0.06, is obtained.

It can be seen in the above figure that the ratio $T_{0.2-t}/T_{0.2-i}$ tends to a value of ~ 0.68 when the relative submersion $R_c/L_{0.2-i}$ tends to zero, taken from either the positive or the negative side. The results of Van der Meer's measurements for the emerged breakwater are closer to this value, since the measurements were made for the lower parameter $R_c/L_{0.2-i}$. The obvious dependence of parameter $T_{0.2-t}/T_{0.2-i}$ on the relative submersion means that the transfer of energy from lower to higher frequencies in a non-linear interaction process depends on the relative submersion $(R_c/L_{0.2-i})$.

The impact of relative submersion $R_c/L_{0.2-i}$ on peak period T_p for smooth breakwaters with submerged and emerged crowns is also presented. The investigations conducted so far suggest that the transmitted peak period is very close to the incident period (Van der Meer et al. 2000, 2005). These conclusions have been confirmed here, namely, that parameter T_{p-t}/T_{p-i} for a submerged breakwater (Figure 8, left) ranges from 1.0 to 1.15. With regard to emerged breakwaters (Figure 8, right), T_{p-t}/T_{p-i} was found to depend on the relative submersion $R_c/L_{0.2-i}$. The transmitted peak period increased in relation to the incoming period by $\sim 35\%$ for the shortest waves.

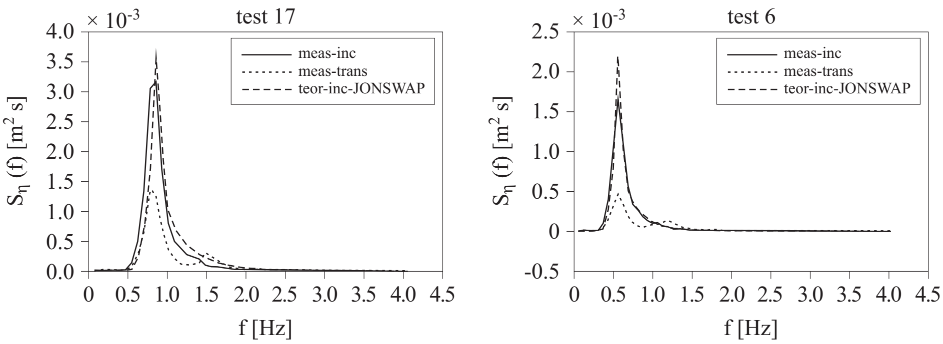


Figure 8. Comparison of the measured incident, theoretical incident (JONSWAP) and transmitted spectra for tests 17 and 6

The figures above present measured incident and transmitted spectra. The theoretical incident JONSWAP spectrum is also shown for comparison.

The agreement between measured and theoretical incident spectra is satisfactory. The same conclusion can be drawn for the other tests from Table 1. The area of the transmitted spectra is reduced because wave breaking and the transition of energy to higher frequencies are evident.

3.2. An empirical model for estimating the reduction in the mean spectral period after a wave has crossed a smooth breakwater

The equation for reducing the coefficient of the mean spectral wave period ($K_{\mathrm{R-T_{0.2}}}$) after a wave has crossed a smooth breakwater reads as follows:

$$K_{\mathrm{R-T_{0.2}}} = \frac{\mathrm{T_{0.2-t}}}{\mathrm{T_{0.2-i}}} = \frac{\sqrt{\mathrm{m_{0-t}/m_{2-t}}}}{\sqrt{\mathrm{m_{0-i}/m_{2-i}}}} = \sqrt{\frac{\mathrm{m_{0-t}}}{\mathrm{m_{0-i}}}}\sqrt{\frac{\mathrm{m_{2-i}}}{\mathrm{m_{2-t}}}}. \tag{1}$$

The first term in the above equation represents the transmission coefficient of the significant wave height over the breakwater:

$$K_{\mathrm{T-H_{m_0}}} = \frac{\mathrm{H_{m_{0-t}}}}{\mathrm{H_{m_{0-i}}}} = \frac{4\sqrt{\mathrm{m_{0-t}}}}{4\sqrt{\mathrm{m_{0-i}}}} = \sqrt{\frac{\mathrm{m_{0-t}}}{\mathrm{m_{0-i}}}}. \tag{2}$$

If equation (2) is inserted in equation (1), the following is obtained:

$$\frac{K_{\mathrm{R-T_{0.2}}}}{K_{\mathrm{T-H_{m_0}}}} = \sqrt{\frac{\mathrm{m_{2-i}}}{\mathrm{m_{2-t}}}}. \tag{3}$$

In practice, the equation of Van der Meer et al. (2003) is usually used for estimating $K_{\mathrm{T-H_{m_0}}}$:

$$K_{\mathrm{T-H_{m_0}}} = [-0.3\mathrm{R_c/H_{m_{0-i}}} + 0.75[1 - \exp(-0.5\xi_{\mathrm{op}})]] \tag{4}$$

with a minimum of 0.075 and a maximum of 0.8 (see list of symbols). This paper uses the range of the above equation from 0.075 to 1.0. The second term in the above equation regulates the impact of wave steepness and breakwater slope over the breaker parameter ξ_{op}. For the usual breakwater slope of 1:2, it is found that equation (4) varies in the range $\mathrm{D}K_{\mathrm{T-H_{m_0}}} = 0.15$, owing to the change of wave steepness $\mathrm{H_{m_{0-i}}/L_{op-i}} = 1/10$–$1/30$. Therefore, the variability of the second member will be neglected and the value of 0.51, estimated for the steepness $\mathrm{H_{m_{0-i}}/L_{op-i}} = 1/20$, can be taken instead. The influence of such a reduction on the final accuracy of the empirical model is minor; in any case we shall simplify the model. The following equation is obtained:

$$K_{\mathrm{T-H_{m_0}}} = [-0.3\mathrm{R_c/H_{m_{0-i}}} + 0.51]. \tag{5}$$

Coefficient K may be defined from equation (3) and equation (5):

$$K = \frac{K_{\mathrm{R-T_{0.2}}}}{[-0.3\mathrm{R_c}/\mathrm{H_{m_{0-i}}} + 0.51]}. \tag{6}$$

The coefficient represents the ratio $\sqrt{\mathrm{m_{2-i}}/\mathrm{m_{2-t}}}$ and contains information on how much the wave spectrum area has been reduced as a result of the waves crossing the breakwater, but also on how much energy has been transformed from lower to higher harmonics, since the definition of the moment is $\mathrm{m_2} = \int_0^\infty \mathrm{f}^2\ \mathrm{S}_\eta(\mathrm{f})\mathrm{df}$. These impacts will not be studied in this paper, however.

3.2.1. Derivation of an empirical model for a submerged breakwater

The values of parameter K (eq. (6)) are estimated for every measured $K_{\mathrm{R-T_{0.2}}}$, (which can be estimated for each test from Table 1). The ordered pairs $(-\mathrm{R_c}/\mathrm{L_{0.2}}, K)$ are inserted in the diagram, so the points presented in Figure 9 are obtained.

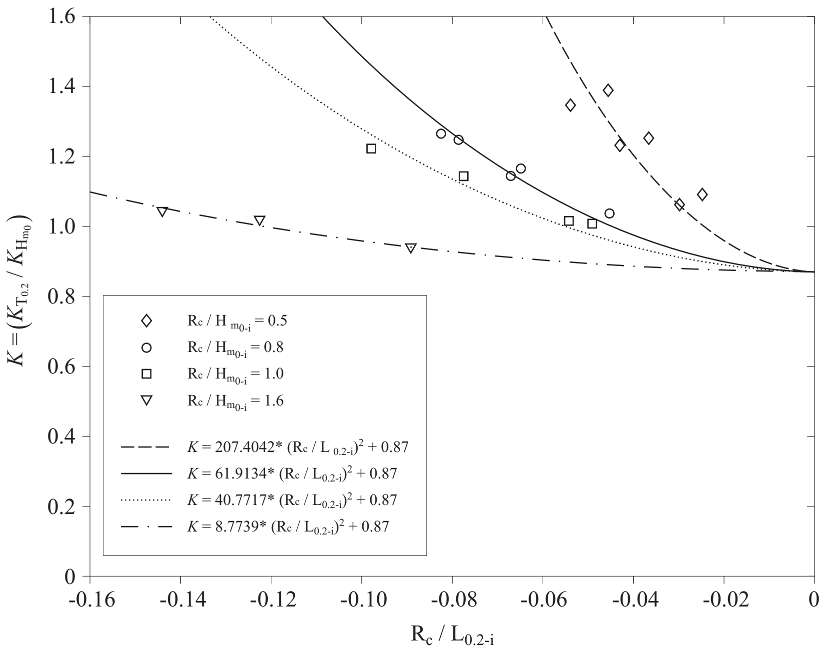


Figure 9. Data fitting of equation (7), for four categories of parameter $\mathrm{R_c}/\mathrm{H_{m_{0-i}}} = 0.5$, 0.8, 1.0 and 1.6, for a submerged smooth breakwater, coefficient $B = 0.87$

The points are arranged according to the parameter $\mathrm{R_c/H_{m0-i}}$, so that four data groups are formed for parameter values of $\mathrm{R_c/H_{m0-i}} = 0.5$, 0.8, 1.0 and 1.6. Measured values with smaller parameter $\mathrm{R_c/H_{m0-i}}$ have larger values of coefficient $K = \sqrt{\mathrm{m_{2-i}/m_{2-t}}}$ because of the smaller wave transmission coefficients $K_{\mathrm{H_{m_0}}}$. Smaller values of $K_{\mathrm{H_{m_0}}}$ mean a larger difference between $\mathrm{m_{2-i}}$ and $\mathrm{m_{2-t}}$. All measured values for each group are reduced when wavelengths grow because of increasing $K_{\mathrm{H_{m_0}}}$. The influence of the period coefficients $K_{\mathrm{T_{0.2}}}$, which are reduced with increasing wavelengths, is minor. In other words, the main reason why K decreases is because the influence of spectral surface reduction (included in $K_{\mathrm{H_{m_0}}}$) is larger than that of non-linear interactions (included in $K_{\mathrm{T_{0.2}}}$). When values of K reach 1, and below 1, this means that non-linear interactions play a significant role.

The function in the form of equation (7) was fitted to each data group:

$$K = A\left(\frac{\mathrm{R_c}}{\mathrm{L_{0.2-i}}}\right)^2 + B\,. \tag{7}$$

It is presumed that all the measured data in the diagram (Figure 9) pass through the same point on the ordinate, which means that the value of the coefficient B in equation (7) will be the same for every data group $\mathrm{R_c/H_{m0-i}} = 0.5$, 0.8, 1.0 and 1.6.

This assumption is necessary because of the lack of measured data in the area around the value $\mathrm{R_c/L_{0.2-i}} = 0$. The consequence of such an assumption is that the final model is not reliable near $\mathrm{R_c/L_{0.2-i}} = 0$. The coefficient B has been determined under the condition that when $\mathrm{L_{0.2-i}} \to \infty$, the first term of equation (7) tends to 0, and is obtained by equalizing equation (6) with equation (7), that is:

$$B = \frac{K_{\mathrm{R-T_{0.2}}}}{[-0.3\mathrm{R_c/H_{m_{0-i}}} + 0.51]}\,. \tag{8}$$

If B is calculated according to equation (8) for four values of $\mathrm{R_c/H_{m_{0-i}}} =$ 0.5, 0.8, 1.0 and 1.6, and for the approximate value $K_{\mathrm{R-T_{0.2}}} \sim 0.68$ (Figure 7), then the values $B = 1.03$, 0.91, 0.84 and 0.69 are obtained. For the final value of coefficient B, the mean value of calculated values is taken, which is $B = 0.87$.

The coefficient A is obtained by fitting the function (eq. (7)) with the constant value of $B = 0.87$ to the data groups, as presented in Figure 9. For the data groups $\mathrm{R_c/H_{m_{0-i}}} = 0.5$, 0.8, 1.0 and 1.6, the coefficients $A = 207.4$, 61.9, 40.7 and 8.8 are obtained. The ordered pairs ($\mathrm{R_c/H_{m_{0-i}}}$, A) are inserted into the diagram and the curve in the form as indicated below is fitted to them:

$$A = A1\ \exp[B1\ (\mathrm{R_c/H_{m_{0-i}}})]\,. \tag{9}$$

Coefficients $A1 = 1280.6$ and $B1 = 3.65$ are obtained.

By equalizing equation (6) and equation (7), in which the function of coefficient A (eq. (9)) has been included, with coefficients $A1$ and $B1$, the empirical equation for estimating the reduction coefficient of the mean spectral wave period when crossing the submerged breakwater is obtained:

$$K_{\mathrm{R-T_{0.2}}} = \left[-0.3\frac{\mathrm{R_c}}{\mathrm{H_{m_{0-i}}}} + 0.51\right] \times \tag{10}$$

$$\times\left[1280.6\,\exp\times(3.65\times(\mathrm{R_c/H_{m_{0-i}}}))\left(\frac{\mathrm{R_c}}{\mathrm{L_{0.2-i}}}\right)^2 + 0.87\right].$$

The above equation is valid, provided that the following limitations are taken into account: maximum $K_{\mathrm{R-T_{0.2}}} = 1$; $-1.6 \le \mathrm{R_c/H_{m_{0-i}}} \le -0.5$; $-0.15 \le \mathrm{R_c/L_{0.2-i}} \le -0.02$; $0.034 \le \mathrm{H_{m_{0-i}}/L_{s-i}} \le 0.091$.

3.2.2. Derivation of an empirical model for an emerged breakwater

The empirical model presented below was derived for an emerged smooth breakwater, based on measurements conducted by Van der Meer et al. (2000) in the wave channel of the Delft Hydraulics company. The measurements are given in Table 2, and the measured reduction coefficients of the mean spectral wave period $K_{\mathrm{R-T_{0.2}}}$, which depend on the relative submersion $\mathrm{R_c/L_{0.2-i}}$ are shown in Figure 7.

For each measured $K_{\mathrm{R-T_{0.2}}}$, the values of parameter K are estimated according to equation (6). The ordered pairs ($\mathrm{R_c/L_{0.2}}$, K) are inserted into the diagram and the points presented in Figure 10 obtained. The function of the form equation (7) should be fitted to the points, assuming that the coefficient $A = \text{const}$, i.e. that it does not depend on the parameter $\mathrm{R_c/H_{m_{0-i}}}$.

In the case of an emerged breakwater, the coefficient B is defined differently than in the case of a submerged breakwater. In data for the emerged crown, the measured coefficient $K_{\mathrm{R-T_{0.2}}}$ is very close to the ordinate, with $\mathrm{R_c/L_{0.2}} = 0.003$ and parameter $\mathrm{R_c/H_{m_0}} = 0.05$. B is determined provided that $\mathrm{L_{0.2}} \to \infty$ in equation (7), so that the first term of equation (7) tends to 0, and equation (8) is obtained. By inserting

Table 2. Wave parameters used for measurements in the study by Van der Meer et al. (2000) and measurement of transmitted wave parameters; B_b – crown width, water depth $d = 0.29$–0.37 m, breakwater slope 1:4

$B_{b=0.13}$ m							
		measured incident			measured transmitted		
Test	R_c [m]	$H_{m_{0-i}}$ [m]	$T_{0.2-i}$ [s]	T_{p-i} [s]	$H_{m_{0-t}}$ [m]	$T_{0.2-t}$ [s]	T_{p-t} [s]
1	0.09	0.086	1.12	1.35	0.005	0.99	1.80
2	0.07	0.097	1.19	1.47	0.017	0.87	1.72
3	0.05	0.111	1.27	1.54	0.031	0.87	1.58
4	0.03	0.122	1.32	1.64	0.041	0.88	1.71
5	0.01	0.135	1.39	1.73	0.054	0.97	1.76

$B_{b=0.03}$ m							
		measured incident			measured transmitted		
Test	R_c [m]	$H_{m_{0-i}}$ [m]	$T_{0.2-i}$ [s]	T_{p_i} [s]	$H_{m_{0-t}}$ [m]	$T_{0.2-t}$ [s]	T_{p-t} [s]
1	0.09	0.089	1.11	1.37	0.005	0.85	1.81
2	0.07	0.102	1.19	1.47	0.017	0.81	1.77
3	0.05	0.115	1.26	1.56	0.029	0.85	1.65
4	0.03	0.127	1.32	1.67	0.041	0.88	1.71
5	0.03	0.125	1.24	1.71	0.038	0.86	1.82
6	0.01	0.138	1.39	1.72	0.055	0.93	1.79

the values $R_c/H_{m_{0-i}} = 0.05$ and measured values $K_{R-T_{0.2}} \sim 0.68$ (Figure 7) in equation (8), $B \approx 1.35$ is obtained. Equation (7) with coefficient $B = 1.35$ is fitted to the points in Figure 10 so that coefficient $A = 810.6$ is obtained.

By equalizing equation (6) and equation (7), into which the coefficients $A = 810.6$ and $B = 1.35$ are inserted, the empirical equation for estimating the reduction coefficient of the mean spectral wave period when crossing the emerged breakwater is obtained:

$$K_{R-T_{0.2}} = \left[-0.3\frac{R_c}{H_{m_{0-i}}} + 0.51\right] \times \left[810.6 \times \left(\frac{R_c}{L_{0.2-i}}\right)^2 + 1.35\right]. \quad (11)$$

The above equation is valid provided that the following limitations are taken into account: maximum $K_{R-T_{0.2}} = 1$; $0.05 \leq R_c/H_{m_{0-i}} \leq 1.1$; $0.003 \leq R_c/L_{0.2-i} \leq 0.06$; $0.043 \leq H_{m_{0-i}}/L_{s-i} \leq 0.053$, the first term of equation (11) can be a minimum $[-0.3R_c/H_{m_{0-i}} + 0.51] = 0.075$.

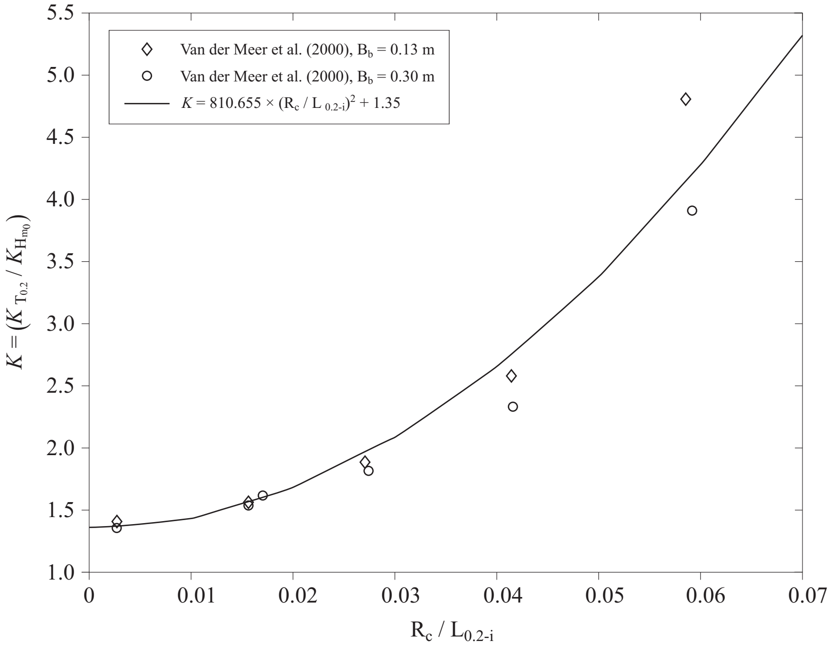


Figure 10. Data fitting of equation (7), for an emerged smooth breakwater, with coefficient A independent of parameter R_c/H_{m_0} and coefficient $B = 1.35$

3.2.3. Verification of the empirical model for submerged and emerged breakwaters

Figure 11 shows the verification of the empirical models for estimating the reduction coefficients of the mean spectral periods when waves cross the submerged and emerged breakwaters (eq. (10) and eq. (11)). The measured coefficient $(K_{R-T_{0.2}})_{meas}$ and the calculated coefficient $(K_{R-T_0})_{calc}$ are compared in the figure by means of equation (10) and equation (11).

The agreement of measurements with the empirical model results for the submerged breakwater is good when the majority of data are in the region of $\mathrm{d}K_{R-T_{0.2}} = \pm 0.05$. The empirical model for an emerged breakwater is formed on the basis of fewer measurements. Therefore, there is weaker agreement between the estimated and measured values than for the results of the submerged breakwater.

Both equations (eq. (10) and eq. (11)) were derived on the basis of a small number of measured data: this is the major weakness of these equations. Nevertheless, we have presented a new approach for calculating the reduction in mean period, which could be a good basis for further investigations of these issues.

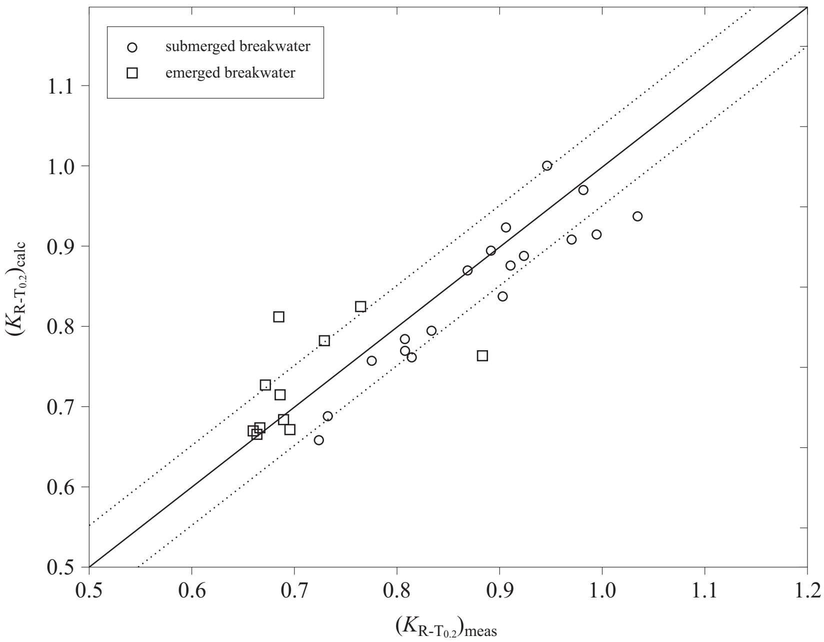


Figure 11. Diagram comparing the measured reduction coefficients of the mean spectral wave period $(K_{\mathrm{R-T_{0.2}}})_{\mathrm{meas}}$ and the values calculated by means of equation (10) and equation (11) $(K_{\mathrm{R-T_{0.2}}})_{\mathrm{calc}}$ for submerged and emerged breakwaters

The application of this empirical model to the design of low-crested structures is limited. It is important to stress that this empirical model was developed from a dataset recorded in a wave flume. In reality, a three-dimensional wave transformation occurs across a breakwater, which means oblique, short-crested incident waves.

Piling-up behind the submerged breakwater is also specific to wave flume tests, which is not the case for real submerged breakwaters with wide gaps along the structure where offshore directed flows occur. Martinelli et al. (2006) compared piling up at breakwaters with narrow gaps (3D laboratory model) with piling up in the wave flume. Those authors found that piling up was approximately 50% smaller when narrow gaps were present. The influence of piling up on measurement accuracy was not tested. The piling up measured in the laboratory investigations conducted in this work is presented in Table 3. The values were calculated in the same way as the average surface oscillations. The first parts of the time series, which are statistically unsteady, were cut off.

The use of the mean spectral period $\mathrm{T}_{0.2} = (\mathrm{m}_0/\mathrm{m}_2)^{0.5}$, based on the 2nd order spectral moment, could be questionable, because it is very sensitive to

Table 3. Piling up measured in the wave flume tests

Test	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
Measured piling up [mm]	0.6	−0.2	0.9	4.8	6.2	6.9	9.5	10.5	11.7	0.4	0.4	0.2	0.6	0.9	1.5	0.6	2.8	4.2

high frequency disturbances. The EU CLASH Project suggested employing either $T_{0.1} = (m_0/m_1)$ or $T_{0,-1} = (m_{-1}/m_0)$ as the most stable index for the period. Therefore, the same calculations as those presented for Figure 7 were conducted but with suggested periods of $T_{0,1}$ and $T_{0,-1}$. As the results are very similar to those presented in Figure 7, the period $T_{0.2}$ was chosen because of the clear comparability with statistical periods.

4. Conclusion

Experimental investigations in a wave channel were conducted with a smooth submerged breakwater. Tests showed, in general, that when waves cross the breakwater the statistical wave periods $T_{1/10}$, T_s and T_m are reduced. The reduction of wave periods depends on the relative submersion, i.e. on the ratio of the breakwater crown submersion and the incoming wave length R_c/L_{s-i}. There is a greater reduction in wave periods for lower relative submersion values, so that the mean wave period T_m is reduced by as much as 25% in relation to the incoming mean period. The mean wave periods are reduced the most, and $T_{1/10}$ ($\sim 5\%$) the least. Consequently, the interrelations of representative statistical periods also change. Instead of the standard relations $T_{max} \approx T_{1/10} \approx T_s \approx 1.1$–$1.2\ T_m$, these relations behind the breakwater tend to $T_{max} \approx T_{1/10} \approx T_s \approx 1.5\ T_m$.

It was also concluded that the mean wave periods calculated by both the statistical approach (zero up-crossing) T_m and the spectral approach $T_{0.2}$ have approximately the same values behind the breakwater, i.e. wave spectral deformation does not affect the calculation of the mean spectral period $T_{0.2}$. The mean spectral period $T_{0.2}$ depends on the relative submersion $R_c/L_{0.2-i}$ and is reduced as submersion approaches zero for both submerged and emerged breakwaters. It is estimated that the greatest reduction in period $T_{0.2}$ when waves cross the smooth breakwater occurs when the relative submersion is $R_c/L_{0.2-i} \sim 0$ and amounts to $\sim 70\%$ of the value of the incoming mean period.

The peak period T_p increases or remains the same when the waves cross the smooth submerged breakwater. As far as the emerged breakwater is concerned, there is a dependence of the peak period T_p, and the relative submersion $R_c/L_{0.2-i}$. By increasing the relative submersion, the peak period T_p increases by up to 35% in relation to the incoming peak period.

The empirical model is formed for estimating the reduction in the mean spectral period when the waves cross submerged and emerged smooth breakwaters. For the incoming wave parameters and the depth in the breakwater crown, the model provides the values for the reduction coefficients $K_{R-T_{0.2}}$. As the model was derived from a restricted number of measurements, additional measurements will be necessary, particularly in the zone of relative submersion $R_c/L_{0.2-i} \sim 0$.

Measured reduction coefficients of the mean period agree well with the calculated values.

List of symbols:

H_{max}	maximum wave height, [m], (zero up-crossing),
$H_{1/10}$	1/10th wave height, [m], (zero up-crossing),
H_s	significant wave height, [m], (zero up-crossing),
H_m	mean wave height, [m], (zero up-crossing),
T_{max}	maximum wave period, [s], (zero up-crossing), which corresponds to the maximum wave height,
$T_{1/10}$	1/10th wave period, [s], (zero up-crossing), which corresponds to one tenth of the greatest wave heights,
T_s	significant wave period, [s], (zero up-crossing), which corresponds to one third of the greatest wave heights,
T_m	mean wave period, [s], (zero up-crossing),
H_{m_0}	significant wave height, [m], $H_{m_0} = 4\sqrt{m_0}$,
$T_{0.2}$	mean wave period, [s], $T_{0.2} = \sqrt{m_0/m_2}$,
m_0, m_2	zero and second spectral moment, $m_0 = \int_0^\infty S(f)df$, $m_2 = \int_0^\infty f^2\, S(f)df$,
$S_\eta(f)$	wave spectra, [m^2 s],
T_p	peak wave period, [s],
$L_{0.2}$	mean wave length at the toe, [s], $L_{0.2} = (gT_{0.2}{}^2/2\pi)\ \tanh(2\pi d/L_{0.2})$,
L_m	mean wave length at the toe, [s], $L_m = (gT_m{}^2/2\pi)\ \tanh(2\pi d/L_m)$,

s_{op}	wave steepness, [1], $s_{op} = H_{m0}/L_{op}$,
L_{op}	offshore incident wave length, [m],
$K_{T-H_{m0}}$	transmission coefficient of significant wave height, [1],
$R_{R-T_{0.2}}$	reduction coefficient of mean spectral wave period, [1],
ξ_{op}	breaker parameter, $\xi_{op} = \tan\alpha\sqrt{s_{op}}$,
a	breakwater slope angle, [°],
K	ratio of measured reduction coefficient of wave period and calculated transmission coefficient of wave height, [1],
B_b	breakwater crown width, [m],
R_c	crown height in relation to water level, positive if emerged, negative if submerged, [m].

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