Nonlinear transformation of waves above submerged structures

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Abstract

On the base of laboratory experiments the nonlinear wave transformation above submerged rectangular permeable and solid bars was investigated. A transmission coefficient and a change of mean wave period as parameters of wave transformation were considered. Both of these parameters can characterize an ability of submerged structure to reduce a wave impact in coastal zone. It was revealed that for decreasing of mean wave period solid submerged bar is more effective, but permeable bar is more effective for decreasing of wave height. The optimal relations for transmission coefficient and change of mean wave period in dependence of parameters of bar and waves were revealed. For decreasing of wave mean period the optimal length of solid bar must be 0.4 of initial wavelength and 0.1 - for permeable bar. For decreasing of wave height the length of bar for permeable bar must be 0.21 of initial wavelength and for solid bar - 0.55. It was revealed that maximal decreasing of mean wave period will be at relative depth of bar 1.25 independently of permeability of bar. The optimal relation between transmission coefficient and changes of mean wave period depends on wave steepness.

1. Introduction

Nomenclature

| Symbol | Description                  |
|--------|------------------------------|
| H_s in | significant wave height before bar |
| H_s tr | significant wave height after bar |
| K_tr  | transmission coefficient     |
| S     | wave spectrum                |
| f     | frequency                    |
A protection of the shores against the waves is an important problem of coastal engineering. In modern practice of coastal engineering there is a necessity of searching of innovative solutions, which protect the shore and at the same time save ecological environment in coastal zone. A submerged structures as breakwaters satisfy of these requirements. In this case wave breaking and decreasing of wave energy are main features taking in account when wave transforming above submerged structure. Than less is the water depth above the top of submerged structure than more intensive will be wave breaking and reducing of wave energy. Another effect of wave transformation above submerged structure is nonlinear wave decomposition and formation of secondary waves consisting from highest nonlinear wave harmonics that decreases the effect of wave impact on the shore too.

The basic nonlinear-dispersive mechanism of formation of secondary waves is described in details by many researchers (for example, Johnson et al.(1951), Beji and Battjes (1993), Masselink (1998), Van der Meer et al.(2000), Kuznetsov and Saprykina (2009, 2012)). Secondary waves arise as separate peaks on a surface of initial wave and consist from higher harmonics of main wave motion. Higher harmonics are formed due to nonlinearity during the wave propagation above top of submerged structures on shallow water. Secondary waves are well visible behind the underwater structures (fig.1).

A decomposition of initial waves and formation of secondary waves leads to decreasing of mean wave period. It has many advantages for coastal engineering: 1) it can suppress or at least detain wave breaking and, accordingly, energy dissipation to a coastal line; 2) the shorter waves less affect on the bottom relief and on technical constructions; 3) decreasing of wave period permit to use the floating breakwaters for additional attenuation of wave motion (Kuznetsov, Saprykina (2013)). So possibility to decrease the mean wave period may be very useful for innovation methods of shore protection and can be considered as additional feature of underwater structures as breakwaters.

As the evaluative criteria of wave transformation above submerged structure transmission coefficient and decreasing of mean wave period can be used. The first one defines of influence of underwater structure on waves determined by its reflection and breaking. The second one defines influence of nonlinear-dispersive mechanism on wave transformation.

The main purpose of this work is to reveal how the transmission coefficient and mean period of wave behind the bar depends on parameters of bar and of initial waves.

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| Symbol | Definition |
|-------|------------|
| $T_m$ | mean wave period |
| $L$   | length of wave |
| $L_{bar}$ | length of bar |
| $d_{bar}$ | water depth above bar |

Fig. 1. Example of secondary waves - separate peaks on surface of initial waves (fragment of wave record in laboratory experiment)
2. Methods

The laboratory experiment was performed in the flume of research center «Sea Coasts» in Sochi, Russia. The length of flume 22 m, the width – 0.6 m, the depth – 1 m. A transformation of initially pseudo monochromatic waves above solid and permeable bar was investigated.

Solid bar of length 1 m and height 0.17 m was placed on horizontal bottom. Water depth was 0.34 m. During experiment, 3 capacity wave gauges were used to measure the wave transformation processes. Duration of wave records was 1-2 min with sampling frequency 17 Hz (fig 2a).

Permeable bar was constructed from tetrapod. The length of bar was about 0.4 m and the height – about 0.14 m. This bar was placed on inclined bottom with slope 0.022. Water depth was 0.4 m. For a measurements of wave transformation 14 capacity wave gauges were used (fig. 2b). Duration of wave records was 2-3 min with sampling frequency 50 Hz.

\[
K_{tr} = \frac{H_{s \text{tr}}}{H_{s \text{in}}},
\]

where indexes tr and in means transformed waves behind the bar and the initial waves before the bar,

\[
H_{s} = 4\sqrt{m_0}
\]
\[ m_0 = \int S df \]  

The mean wave period was defined as:

\[ T_m = \frac{\int S df}{\int f df} \]  

Changes of mean wave period and transmission coefficient were evaluated on the base of analysis of wave chronograms, records by nearest wave gauges before and after bar: for solid bar it was gauges 1 and 2, for permeable bar – gauges 5 and 6 (fig.2). The dependencies of mean wave period and of transmission on the next dimensionless parameters of bar and initial waves were studied:

- relative wave length - length of structure to length of waves on deep water: \( \frac{L_{bar}}{L} \);
- relative depth - water depth above bar to significant wave height before bar: \( \frac{d_{bar}}{H_{s in}} \);
- steepness of waves before bar: \( \frac{H_{s in}}{L} \).

3. Discussion of results

Laboratory experiments revealed reducing of transmission coefficient with decreasing wavelength and increasing of wave steepness (fig.3). Minimal transmission coefficient for permeable and solid bar is about 0.58. It is at \( L_{bar}/L=0.21 \) for permeable bar and at \( L_{bar}/L=0.55 \) for solid bar. Transmission coefficient decreases with increasing of wave steepness up to 0.09. But for waves with steepness more than 0.09 increasing of the transmission coefficient with increasing of length of bar is observed. For these steep waves wave breaking occurs only at the beginning of bar and waves shoaling over the bar without breaking that leads to increasing of waves height after the bar.

![Fig. 3. Dependence of transmission coefficient on the relative wavelength and wave steepness (a – permeable bar, b – solid bar)](image)

The permeability of bar strongly influence on changing of mean wave. For some waves passing over permeable bar the mean wave period does not change (\( T_2/T_1 \) close to one, fig.4 a). For solid bar the mean wave period always decreases at least up to 4% (fig.4 b). Decreasing of mean wave period for both bars is more effective for waves with steepness less than 0.09. For waves with steepness \( 0.03<H_{s in}/L<0.09 \) solid bar better reduces mean wave period. For waves with steepness more than 0.09 reducing of mean wave period is not more 5% for permeable bar and 20% for solid bar. For these waves with increasing of relative length of bar the mean wave period practically does not changes. It can be explained by dissipation of highest nonlinear harmonics during propagation of steep waves over the bar. In
general, permeable bar decreases mean wave period not more than 1.3 times (minimal $T_2/T_1$ is 0.77), but solid bar decrease mean wave period 1.5 times (minimal $T_2/T_1$ is 0.65). Maximal decreasing of wave period, when the waves are passing above permeable bar, occurred at wavelength which is 12.5 times greater than length of bar ($L_{bar}/L=0.08$). Solid bar more effective for wavelength which is in 3 times greater than length of bar ($L_{bar}/L=0.32$).

![Fig. 4. Dependence of change of mean wave period on the relative wavelength and wave steepness (a – permeable bar, b – solid bar)](image)

![Fig. 5. Dependencies of transmission coefficient on the relative wave height and on wave steepness (a – permeable bar, b – solid bar)](image)

Transmission coefficient and change of main period depend on relative water depth above the bar – a relation of depth over the bar to significant wave height before the bar (fig.5, 6). For both types of bar the less is relative water depth and the more is steepness of waves the less is transmission coefficient (or less wave height after bar). Decreasing of mean wave period is maximal at relative water depth above bar about 1.25. At this relative water depth process of a generation of higher nonlinear wave harmonics will be prevail on dissipation process. It occur for the waves their steepness is less than 0.03 during propagation over permeable bar and for the waves their steepness is $0.03 < H_s/L < 0.09$ during propagation over solid bar.
In fig. 7 the dependences of changes of mean wave period on transmission coefficient for both types of bars are shown. It is visible that wave steepness influences on optimal relations between transmission coefficient and changes of mean wave period. Optimal means the minimum of transmission coefficient and maximum decreasing of mean period. The best optimal relations between the transmission coefficient and the changes of mean wave period for different steepness of waves are given in Table 1 for solid bar and in Table 2 for permeable bar.

Table 1. The transmission coefficient and the changes of mean wave period for different steepness of waves, solid bar.

| wave steepness (Hₚₗ/L) | 0.01<Hₚₗ/L<0.03 | 0.03<Hₚₗ/L<0.09 | 0.09<Hₚₗ/L<0.13 |
|------------------------|-----------------|-----------------|-----------------|
| T₂/T₁                  | 0.72            | 0.67            | 0.77            |
| Kᵣ                     | 0.76            | 0.76            | 0.74            |
Table 2. The transmission coefficient and the changes of mean wave period for different steepness of waves, permeable bar.

| wave steepness (H_s/L) | T2/T1 | Ktr |
|------------------------|-------|-----|
| 0.01<H_s/L<0.03        | 0.79  | 0.89 |
| 0.03<H_s/L<0.09        | 0.86  | 0.74 |
| 0.09<H_s/L<0.13        | 0.95  | 0.58 |

So, for permeable bar the more is decreasing of mean period (21%) the more is transmission coefficient (0.89). For solid bar such dependence is not revealed. The transmission coefficient is practically the same (0.74-0.76) for all of changes of mean wave period and wave steepness. For waves of steepness 0.03<H_s/L<0.09 both decreasing of the mean wave period and wave height will be strongest for permeable and solid bars. The underwater bar can reduce the mean wave period on 14% (permeable bar) and 33% (solid bar), wave height - on 36 and 34 %, respectively. Taking in account both of parameters (transmission coefficient and changes of the mean period) as a wave impact mitigation in coastal zone, a water depth above submerged structures can be deeper on ~ 30% (d_bar/H in ~1) than if only transmission coefficient would be considered (d_bar/H in ~ 0.7). This is important for recreation potential of coastal zone because, for example, there will no restrictions of waterway for yachting and small boats.

4. Conclusion

Experimental investigation of waves transforming above submerged bar have testified the possibility of decreasing not only wave height, but the mean period of waves also.

For decreasing of the mean wave period solid impermeable bar is more effective. For decreasing of wave mean period the length of solid bar must be about 0.32 of initial wavelength, and about 0.08 - for permeable bar. For decreasing of wave height the length of bar for permeable bar must be 0.21 of initial wavelength and for solid bar - 0.55.

It was revealed that maximal decreasing of mean wave period will be at relative depth of bar 1.25 independently of permeability of bar.

The optimal relation between transmission coefficient and changes of mean wave period depends on wave steepness. For waves of steepness 0.03<H_s/L<0.09 both of the mean wave period and wave height will be decreased: the mean wave period can be reduced on 14% (permeable bar) and 33% (solid bar), wave height - on 36 and 34 %, respectively.

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