WAVE TRANSMISSION BELOW BREAKWATERS WITH SEMI-IMMERSED CURTAIN

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1. Abstract

Breakwaters with semi-immersed curtains are suitable for locations with low to moderate wave conditions (Hs≤1.2-1.4m, fetch≤5-10km). Such structures enable water circulations through the body of breakwater and this way better water quality in closed port basin. The wave transmission through the body of breakwater depends on the curtain immersion, water depth and wave length. Investigations on wave transmission for regular waves have already been conducted and used in engineering practice for years. The lack of the knowledge is about wave transmission for irregular waves which are in their hydrodynamics much closer to the real wind surface waves. This paper gives results of laboratory investigations in wave flume for irregular waves and their comparison to the models developed for regular waves. The paper gives relations between transmission and reflection coefficients, energy losses and transmission of wave periods.

Keywords: permeable breakwater, transmission coefficients, reflection coefficients, semi-immersed curtain, wave period transmission

2. Introduction

City ports and marinas have interest to maintain high seawater quality to attract tourists and give pleasant environment. It can be made a distinction between passive and active measures for the improvement of water quality. The active measures cover forced water circulation by pumps or water aeration where certain amount of energy should be invested. The passive measures cover several types of permeable breakwater structures such as rubble mound breakwater with flushing culverts, breakwaters with semi-immersed curtain and pontoon breakwaters. The wave transmission below breakwaters with semi-immersed curtain will be described hereafter.

To enable better circulation between outer sea and closed water basin of the port engineers used to design openings in the breakwaters’ body or even applied the openings along the total breakwater length if wave clime permits such measure. One of the special structural measures is application of the semi-immersed curtain at the whole breakwater length or as just one restricted section. The most important functional parameter of such
structure is transmission of wave energy at the port side of immersed structure.

The transmission coefficient is a function of the following parameters:

\[ C_T = f (T_p, L_p, H_s, d, t, H_s/L_p, t/d, t/L_p, d/L_p) \]  

\[ \text{eq. 1} \]

- \( T_p \) - peak wave period [s]
- \( L_p \) – peak wave length [m]
- \( H_s \) – significant wave height [m]
- \( d \) – water depth [m]
- \( t \) – wall submergence [m]
- \( H_s/L_p \) – wave steepness [-]

![Figure 42 Definition sketch](image)

The energy of the incoming wave \((E_I)\) can be divided into three parts: transmitted energy \((E_T)\), reflected energy \((E_R)\) and the lost energy \((E_V)\). The loss of energy on the immersed wall includes the dissipation of wave energy through internal friction and friction at the boundary between the media (e.g. on the surface of the wall), wave energy dissipation in the process of the wave breaking and energy losses due to the creation of vortex at the bottom edge of the wall.

Direct measurement of energy losses cannot be carried out. Energy losses can only be indirectly determined from the energy balance. Energetic equilibrium for the two-dimensional case of the structure takes the general form:

\[ E_I = E_T + E_R + E_V \]  

\[ \text{eq. 2} \]

For the energy fraction of the individual parts of the total incoming energy, reformulating the eq. 2 gives:
By using the first order wave theory, according to eq. 3., proportion of the individual parts of the total incoming energy can be expressed as:

\[ C_T^2 = \frac{E_T}{E_I} = \left(\frac{H_T}{H_I}\right)^2 \]  

\[ C_R^2 = \frac{E_R}{E_I} = \left(\frac{H_R}{H_I}\right)^2 \]  

\[ C_V^2 = \frac{E_V}{E_I} = \left(\frac{H_V}{H_I}\right)^2 \]

Fictive loss of wave height \( H_V \) which is given in eq. 6 combines impacts of previously mentioned energy dissipation processes. Considering these relationships, the balance on the immersed wall reads:

\[ 1 = C_T^2 + C_R^2 + C_V^2 \]  

This follows the term for energy loss \( E_V/E_I \) on the immersed wall:

\[ E_V/E_I = \left(1 - C_T^2 - C_R^2\right) \]  

Hoffmann (1967) promoted the Macagano expression for cuboid, which was analyzed as a semi-permeable breakwater. Introduction of an effective length \( l_e \) in this equation enabled its use for the immersed wall [1,2]. Therefore, the transmission coefficient takes form of:

\[ C_T = \frac{1}{\sqrt{1 + \left(\frac{l_e}{d} \cdot \frac{2\pi d}{L} \cdot \sinh \frac{2\pi d}{L} \cdot 2 \cdot \sinh \frac{2\pi d(\frac{d-t)}{L}}\right)^2}} \]  

As previously explained, the effective length \( l_e \) does not apply only to the geometric dimensions of the semi-permeable breakwater, but also to the total energy losses. The parameter \( l_e/d \) for the transmission coefficient calculation according to eq. 9 can be found by using graph at Figure 43 [3]. The eq. 9 is valid for the relative water depth \( 0.10 < d/L < 0.8 \), and the immersion ratio of the plate and the water depth \( t/d > 0.1 \).
In Wiegel (1960) a simple analytic expression for the transmission coefficient was defined [4]. The term was given for monochromatic waves, without overtopping, together with the assumption that there is no energy loss (due to friction, the creation of the vortex, etc.) and has the form of:

$$K_{transm} = \sqrt{\frac{2k(d-t)}{\sinh 2kd} + \frac{\sinh 2k(d-t)}{\sinh 2kd} \frac{2kd}{\sinh 2kd}}$$  \hspace{1cm} \text{eq. 10}$$

where \(k\) is a wave number.

The other equations similar to those presented above are developed in the past but are developed only for the monochromatic waves. Equations from Glazik (1969), Schmidt (1980), Pezzoli (1962), Lappo (1962) should be highlighted here [5–8]. The main aim of this paper is to compare measurements conducted for spectral waves and equations originally developed for monochromatic waves by Hoffman (1967) and Wiegel (1960) [1,4].
3. Methods

The wave channel model is located in the Hydraulic Laboratory of the Faculty of Civil Engineering University of Zagreb. The length of the wave channel is 18.64 [m], the width is 1 [m] and the height is 1.1 [m]. The flume has a constant column of water of 0.6 [m]. At 12.51 [m] from the beginning of the wave channel there was the semi-immersed barrier (plate) that can be vertically moved. Tests were carried out for plate immersion of $t = 0.0$ [m]; 0.05 [m]; 0.1 [m]; 0.15 [m]; 0.2 [m]; 0.25 [m]; 0.3 [m]; 0.35 [m]; 0.4 [m].

The waves were produced using a piston type wave generator with the built-in AWACS (ActiveWaveAbsorptionControl System). The electro-hydraulic servo drives the generator plate and generates waves up to $H_s=0.8$ m. The AWACS system can disable unwanted reflection effects from the rear part of the flume. A total of 8 measuring gauges were set up for measurements of water surface movement. The distances of wave gauges from the wave paddle were: G1-5.666 m, G2-6.366 m, G3-6.516 m, G4-6.626, G5-14.946 m, G6-15.646 m, G7-15.796 m, G8-15.906 m.

![Figure 44. Sketch of the laboratory model](image-url)
For the spectral (irregular) waves a total of 108 measurements were performed, i.e. 12 for each individual level of wall immersion “t”. Wave parameters of each of the tests are presented in Table 9.

Table 9 List of wave tests conducted in wave flume; $H_s$-significant wave height, $T_p$-peak period for different submergences $t=0.0 \ [m]$; $0.05 \ [m]$; $0.1 \ [m]$; $0.15 \ [m]$; $0.2 \ [m]$; $0.25 \ [m]$; $0.3 \ [m]$; $0.35 \ [m]$; $0.4 \ [m]$

<table>
<thead>
<tr>
<th>TEST</th>
<th>$H_s \ [m]$</th>
<th>$T_p \ [s]$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.024</td>
<td>0.73</td>
</tr>
<tr>
<td>2</td>
<td>0.024</td>
<td>0.76</td>
</tr>
<tr>
<td>3</td>
<td>0.027</td>
<td>0.8</td>
</tr>
<tr>
<td>4</td>
<td>0.032</td>
<td>0.83</td>
</tr>
<tr>
<td>5</td>
<td>0.042</td>
<td>0.98</td>
</tr>
<tr>
<td>6</td>
<td>0.050</td>
<td>1.07</td>
</tr>
<tr>
<td>7</td>
<td>0.061</td>
<td>1.21</td>
</tr>
<tr>
<td>8</td>
<td>0.074</td>
<td>1.3</td>
</tr>
<tr>
<td>9</td>
<td>0.074</td>
<td>1.33</td>
</tr>
<tr>
<td>10</td>
<td>0.077</td>
<td>1.36</td>
</tr>
<tr>
<td>11</td>
<td>0.095</td>
<td>1.5</td>
</tr>
<tr>
<td>12</td>
<td>0.120</td>
<td>1.59</td>
</tr>
</tbody>
</table>

4. Results and discussion

The main question which arises is whether is possible to use empirical equations by Hoffman (eq. 9) and Wiegel (eq. 10), originally developed for monochromatic waves, for estimation of transmission coefficients for spectral waves (real waves in the nature) [1,4]. The comparisons are shown in Figure 45 and Figure 46. In the case of the Wiegel equation the measured values are lower than those calculated, especially in the range of smaller coefficients ($C_{T,\text{theor}}<0.6$) [4]. So it seems that Wiegel equation does overestimates transmission coefficients for spectral waves [4].

In the case of the Hoffman equation, the measured values are lower than those calculated, especially considering the range of the coefficients ($C_{T,\text{theor}}>0.6$) [1]. The similar conclusion should be brought that Hoffman’s equation overestimates transmission coefficients for spectral waves [1]. Due to these irregularities of application of these two equations, further in this paper, the new simple approach will be proposed especially developed for spectral waves.
Figure 45. Comparison of the transmission coefficients $C_{T, \text{theor}}$ calculated theoretically (by Wiegel equation [4]) and measured transmission coefficients $C_{T, \text{meas}}$ in laboratory experiments for spectral waves.

It should be noted also that in the case when the plate immersion is $t/d=0$, measured transmission coefficients are $C_{T, \text{meas}}=0.9$ what is different than theoretical value calculated by both theoretical equations $C_{T, \text{theor}}=1.0$. This difference is caused due to the energy losses produced in interaction between wall and wave crest. Thus, in real conditions, even for ratio $t/d=0$, there is a small amount of energy losses what is neglected by the theoretical equations.

Figure 46. Comparison of the transmission coefficients $C_{T, \text{theor}}$ calculated theoretically (by Hoffman equation) and measured transmission coefficients $C_{T, \text{meas}}$ in laboratory experiments for spectral waves.

According to eq. 2 there should be energy balance achieved when waves pass below the immersed plate. The comparison presented on Figure 47 show relation between measured values of transmission and reflection coefficients. The trend of data reflects clear relationship which is supported by energy balance equation (eq. 2). For the comparison, the theoretical curve of relation between $C_R$ and $C_T$ calculated according to eq. 7 is also presented on the graph. The theoretical curve is given taking an assumption
that energy losses are zero \((E_V/E_I = 0)\).

![Figure 47. Comparison of the measured reflection coefficients \(C_{R,\text{meas}}\) and measured transmission coefficients \(C_{T,\text{meas}}\)](image)

The magnitude of energy losses \(E_V/E_I\) on the immersed plate can be calculated by eq. 8 using measured data of reflected and transmitted coefficients. Values of energy losses are presented at Figure 48. In the range of small parameters \(t/L_p < 0.1\) the energy losses \(E_V/E_I\) monotonically increase up to the value of 0.3 and after that each curve (for different \(t/d\) parameter) have different variation in relation to parameter \(t/L_p\). Average value of energy losses is \((E_V/E_I)_{\text{average}} = 0.22\).

![Figure 48. Energy losses values \(E_V/E_I\) calculated from measured values of reflected \(C_{T,\text{meas}}\) and transmitted \(C_{R,\text{meas}}\) coefficients](image)

In the next section the new empirical approach will be presented for calculation of the transmission coefficient \(C_T\) in the case of spectral waves. Hoffman’s (eq. 9) and Wiegel’s (eq. 10) equations have been developed based on theoretical approach and validated through the experimental measurements presented in Eggert et al 1983 [1,3,4]. In the same work the relation between measured transmission coefficients \(C_{T,\text{meas}}\) and parameter \(t/L\) was investigated for monochromatic waves (from different authors
Hoffman, Glazik and Eggert [1,3,5]. Generally, conclusion was that dispersion of data is large and that parameter \( t/L \), singly, could not be used for description of the \( C_T \). Eggert (1983) also concluded that \( C_T \) should be described exclusively with parameters \( d/L \) and \( d/t \) [3]. Comparison of \( C_{T\text{, meas}} \) and \( t/L_p \) is once again compared but for spectral waves measured in the scope of this research. The results are shown in Figure 49. Together with measured data the exponential empirical function fitted to the measured data is presented at the same graph. The dispersion of the data relative to the fitted curve is relatively small what is proved by high parameter \( R^2=0.9826 \) what means that curve describes measured data well. It should be noted that curve is valid up to the value of \( C_T=0.9 \) as this is a maximal (in average) recorded transmission coefficient for \( t/L_p=0 \). For comparison the curves which describes mean \( C_T \) for channel measurements with monochromatic waves, published by Hoffman, Glazik and Eggert are presented in Figure 49 [1,3,5].

\[
C_T = 1.03 \cdot e^{-8.27(t/L_p)}
\]  
\text{eq. 11}

The range of the equation validity is: \( 0 \leq C_T \leq 0.9; \ 0 \leq t/d \leq 0.8; \ 0.016 \leq t/L_p \leq 0.45; \ 0.13 \leq t/L_p \leq 0.57; \)

Once the empirical equation for transmission coefficient is defined it is possible to define empirical equation for reflection coefficient \( C_R \) by using eq. 7 and mean value of energy loss coefficient \( C_v^2=0.22 \). The resulted curve is presented in Figure 50 together with the results of \( C_R \) measured in the scope of this research. It should be noted that the lowest value of reflection coefficient given by this empirical approach is \( C_R=0.30 \).
In some engineering situations it is practical to have available information about transmitted wave periods. For this purpose, the measured ratio of transmitted and incident peak wave periods ($T_{p,T}/T_{p,I}$) is presented in Figure 51. From measured data it is obvious that increase of the transmitted wave periods occur in comparison to the incident one for larger ratios of $t/L_p$ and equals in maximum 1.41. This shift of transmitted peak wave periods likely occurs due to resistances to the water flow below immersed plate and are manifested as a separation of the water vortexes.

The second important parameter related to wave periods is the ratio of mean transmitted period $T_{0.2,T}$ and mean incident wave period $T_{0.2,I}$. From the results presented at Figure 52, the change of parameter $T_{0.2,T}/T_{0.2,I}$ in relation to parameter $t/L_p$ is visible. It seems that transmitted mean wave periods are larger than incident, when $t/L_p < 0.3$. This phenomenon likely occurs because, for some submergence of the plate $t$, shorter waves from the wave train (with smaller value of wavelength $L$) reflect from the plate what means that only longer waves pass below the plate and cause generally longer wave field (with greater $T_{0.2,T}$). For the ratios $t/L_p > 0.3$ this effect diminishes, and only occur
transmission of waves with smaller $T_{0,2,T}$ than incident $T_{0,2,I}$ as a result of vortexes separation from the end of the plate.

![Figure 52. Change of the mean wave period ratio $T_{0,2,T}/T_{0,2,I}$ in comparison to the ratio $t/L_p$](image)

5. Conclusion

Structures of permeable breakwaters are traditionally used in the seas with poor water circulation and low tidal oscillations range. One of commonly used structures is permeable breakwater with semi-immersed concrete curtain. Until now, the transmission of wave energy below the immersed plate has been investigated but only for monochromatic waves. In this paper, the wave transmission below immersed plate was investigated for spectral waves. Based on the measurements in wave channel results of wave transmission, reflection and energy losses are shown. The comparison of previously developed equations for monochromatic waves and measured waves is provided. The general conclusion is that the existing equations developed for monochromatic waves overestimate transmission coefficients for spectral waves. The new empirical equation was developed, based on measurements in wave channel, for the estimation of transmission coefficients $C_T$ in the case of spectral waves. Also, model for estimation of reflection coefficient is developed and recommendations for transmitted wave periods estimation are given.

References:


