Experimental Studies of Wave Transmission through Single Perforated Sheets and Upright Perforated Wave Filters

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Abstract

In this paper, an experimental solution has been developed for evaluation of transmission coefficients of water waves through single perforated sheets and upright perforated wave filters. Two series of laboratory tests were carried out on single perforated sheets and upright perforated wave filters. Two kinds of perforated sheets and a wide range of wave steepness were used in these tests. The effects of wave and perforated plate parameters were investigated on the coefficient of wave transmission. Moreover, it is shown that the transmission coefficient through single perforated sheets and upright perforated wave filters can be calculated using the wave-screen parameter defined by Chegini (1995). Finally, a new equation is presented to calculate the wave transmission coefficients through these porous structures.

Keywords: Wave transmission, Wave filter, Perforated sheet, Experimental study, Wave dissipation

1. Introduction

The prediction of transmission coefficients through single perforated sheets and upright perforated wave filters plays an important role in the assessment of the behaviour of upright perforated wave absorbers, as well as perforated wall, slotted, and screen breakwaters and this role has been discussed by some investigators (e.g. Massel and Mei, 1977; Dalrymple et al., 1991; Isaacson et al. 1998; Huang, 2007, and Huang and Yuan, 2009). Upright perforated wave filters are composed of rows of perforated sheets aligned normally to the direction of wave propagation. Transmission of water waves through a perforated plate has been studied by many authors (e.g. Chwang and Dong, 1984; Faure, 1992; McBride et al., 1995; Chegini, 1995 and 1997; Isaacson et al., 1998; Chegini and Chegini, 2006; and RostamiNia and Chegini, 2007). Dissipation of wave energy through wave filters has been investigated by a number of researchers. O'Brien and Chaffin (1942) developed a theory to account for the dissipation of wave energy due to the wall friction. They assumed that the attenuation of wave energy is caused by the viscosity in the boundary layers. They used Lamb's theory derived for periodic motion of an infinite plate oscillating parallel to itself in an infinite fluid, to specify the velocity distribution in the boundary layer. O'Brien and Chaffin (1942) computed the loss of wave energy from the obtained velocity distribution. This theory can be used only for plate filters.
Biesel (1952) presented an analytical solution for computing the attenuation of wave amplitude through wave filters. Adding a resistance term governed by Darcy's law to the unsteady form of the Euler equation, he determined the velocity potential and the surface profile of the dissipated wave. The value of a damping coefficient in this approach should be determined experimentally.

Silberman (1954) incorporated the velocity components based on the linear wave theory with the Navier-Stocks laminar dissipation function, to compute the attenuation of wave energy through a wave filter. The rate of wave dissipation was described as a function of wave specifications and an artificial viscosity that should be determined experimentally.

Herbich (1956) carried out a set of experimental investigations on the reflection and attenuation characteristics of solid-plate and wire mesh wave filters. He used the theories developed by O'Brien and Chaffin (1942), Biesel (1950) and Silberman (1954) for comparison with the experimental results. He reported a good agreement between the laboratory data for solid-plate filters and the theoretical results of O'Brien and Chaffin. Herbich did not make a clear conclusion about the integrity of the two other analytical approaches.

Bowers and Herbich (1957) extended Herbich's studies to provide more information for design of wave filters. They undertook small-scale tests on solid plate, perforated plate, and wire mesh filters, as well as large-scale tests on the wire mesh filters. Bowers et al. (1957) concluded that the wave transmission coefficient of plate filters decreases with increasing filter length and increases with increasing plate spacing and wave length. It was observed that the reflection coefficient increases with increasing wave length and decreases with increasing plate spacing. For wire mesh filters, the transmission coefficient increased with increasing wave length and filter porosity and it decreased as the filter length increased.

Goda and Ippen (1963) developed an analytical expression for evaluation of the transmission coefficient through an upright wave filter composed of wire mesh screens. Neglecting the effect of crossing points, they considered the wires as circular cylinders, so that each screen could be regarded as an assembly of two sets of horizontal and vertical cylinders. They assumed that the total wave force on the cylinders is obtained by superposition of drag and inertia forces. They concluded that the sheet spacing has no effect on the wave transmission coefficient and had a significant influence on the wave reflection coefficient. For deepwater waves, the analytical solution showed a good agreement compared with the laboratory data.

Keulegan (1968 and 1973) studied analytically the attenuation of wave energy in a wave filter composed of a series of porous screens. It was assumed that the resistance of a screen is proportional to the square term of the approach velocity to the screen. Establishing a balance between the rate of wave energy propagation and the rate of energy dissipation, he derived an equation to evaluate the transmitted wave height through the wave attenuator. In this approach, the resistance coefficient of the perforated sheet should be determined experimentally.

Chegini (1995) derived a theoretical expression to evaluate the transmission coefficient through single perforated sheets and upright perforated wave filters. His derivation was based on the bulk dissipation of the incident wave energy. He verified the results of his theoretical solution by laboratory test with regular waves. Thomson (2000) carried out a comprehensive hydraulic model test on wave screens constructed of rectangular slots oriented in either horizontal or vertical direction, attached to vertical piles or support structures and he measured wave transmission and reflection coefficient as functions of wave and screen characteristics.

Balaji and Sundar (2003) investigated the performance of two vertical screens formed by
equally spaced pipes in attenuating the incident wave energy using experimental tests.

Wang and Li (2003) proposed solutions to wave transmission and reflection by bottom mounted wave-permeable structures in shallow water. The results of their investigation showed that wave permeable breakwaters with proper absorbing effects could be used as an effective alternative to massive gravity breakwaters in reduction of wave transmission in shallow water condition.

Chegini (2005) extended the method of Liu et al. (1987) to propose a theoretical solution for calculation of wave reflection and transmission coefficients through upright perforated wave filters. He verified the theoretical model by laboratory tests with regular waves.

Krishnakumar et al. (2010) carried out a comprehensive experimental program to assess the characteristics like reflection and transmission coefficients of slotted wave screens formed with a series of horizontally placed circular elements.

The main problem with most theoretical or experimental methods for calculation of coefficients of wave transmission through single perforated sheets or upright perforated wave filters is that they need performing of experimental tests to calculate empirical parameters involved in these methods. However, in this paper, a simple and applicable method has been presented to calculate this coefficient without the need of carrying out additional tests.

2. The Wave-Screen Parameter

Chegini (1995 and 2001) introduced the wave-screen parameter to describe the hydraulic responses of single perforated sheets. This parameter is defined as:

$$\Gamma = \alpha / \sqrt{H_i/L_o}$$

where:
$$\alpha = c_d p$$
$c_d$ discharge coefficient of perforated sheet

$\rho$ porosity of perforated sheet

$H_i$ incident wave height

$L_o$ deepwater wave length

This parameter is comparable with the surf similarity parameter, which is used for sloping porous structures. It should be noted that the screen factor, $\alpha$, is indeed a representative of the screen characteristics. Therefore, for a thick perforated barrier, the effect of barrier thickness should also be incorporated in equation (1).

The discharge coefficients of screen perforations can be evaluated from the following empirical formula from Dailey et al., (1966) (also used by Mei et al., 1974):

$$c_d = 0.6 + 0.4 (A_p/A)^2$$

where $A_p$ and $A$ are the perforated and the total area of the screen, respectively.

3. Experimental Studies

Two series of experimental tests were performed on single perforated sheets and upright perforated wave filters. The first set of tests were carried out in the 0.9 m wide wave flume of the Water Research Laboratory of the University of New South Wales (WRL). Transmission coefficients were measured for single perforated sheets and wave filters composed of two and four perforated plates of the same porosity. The screens were aligned normally to the direction of wave propagation. All the tests were undertaken with a water depth of $h=0.8$ m. The wave periods were 1.25, 1.35, 1.50, 1.75 and 2.50 seconds. The transmission coefficients were measured for waves of steepness ratios ranging from 0.003 to 0.1. A permeable slopping wave absorber made of artificial horse hair was installed at the end of the flume to attenuate the energy of waves transmitted through wave filters (Chegini, 1993). The reflection coefficients were calculated from the "two probes technique" reported by Thornton and Calhoun (1972).

Two kinds of porous sheets were used for the tests on single perforated sheets: expanded metals of 26,
42, and 58 percent porosity and perforated plates of 23, 40 and 62 percent porosity. The diameters of screen perforations for sheets of 23, 40 and 62 percent porosity were 1.6, 6.35 and 7.94 mm, respectively. Laboratory tests on wave filters were performed using perforated plates of 40 and 62 percent of porosity.

The second set of tests were carried out in the 32.5 m length, 5.5 m wide and 1 m deep wave flume of Soil Conservation and Watershed Management Research Center (SCWMRC), Islamic Republic of Iran on single perforated sheets. This flume is divided into three sections (Fig. 1). The tests were performed in the middle section of the flume. The coefficients of wave reflection and transmission were measured using five wave gauges installed in front and the rear of the perforated sheet (Fig. 2). Goda’s method was employed to calculate the reflection and transmission coefficients (Goda and Suzuki, 1976). To prevent the reflection of waves from the end wall of the flume, a gravel beach absorber was used. The porosity of the sheets were 21, 44 and 48 percent. The tests were carried out using regular waves of 1.25 to 2.5 seconds period. The wave heights ranged from 7.6 to 18.4 centimeters (RostamiNia and Chegini, 2008).

4. Experimental Results

The experimental tests showed that the transmission coefficient decreases with increasing wave steepness. The theoretical results demonstrated that the spacing between the perforated sheets did not have a significant effect on the coefficient of wave transmission (Chegini, 1995). Therefore, this coefficient might be described as a function of the wave-screen parameter, defined in equation (1).

Figure (2) depicts the variation of transmission coefficient as a function of the ratio of wave-screen parameter to the number of plates for single perforated sheets and wave filters composed of two and four perforated plates. The data of Hattori (1972), Faure (1992), McBride et al. (1993), Chegini (1995) and RostamiNia and Chegini (2007) were employed for the case of wave transmission through single perforated sheets. As shown figure 2, the wave transmission increases as the wave-screen parameter increases.

Considering all data obtained from these sources, the wave transmission coefficient from single perforated sheets or upright perforated wave filters can be calculated from the following equation (Fig. 2):

$$K_t = \tanh(1.1 \times 0.5)$$

with $R^2=0.85$ and RMSE=0.07

where $X = \Gamma/n$, and $n$ is the number of sheets in the filter.

It should be mentioned that due to a wide range of wave steepness that were used in different experimental tests by the above mentioned investigators and various porosities of screens which were employed in these tests, equation (5) could be used reliably for calculation of wave transmission through upright perforated wave
filters consisting of perforated plates/screens of any arbitrary screen porosity and against waves with different wave period or height. Also, Chegini (1995) had shown before that the wave-screen parameter could be used as a criterion for efficient design of upright variable porosity wave absorbers, given that for effective dissipation it was necessary that:

\[ \Gamma_{\text{wave-first screen}} \geq 1.8 \]  

(4)

He also demonstrated that the wave energy dissipation for a perforated sheet could be classified into three regions as a function of the wave-screen parameter, which are: i) high dissipation \( (\Gamma < 1.6) \), ii) intermediate \( (1.6 < \Gamma < 6) \), and iii) non-dissipative \( (\Gamma > 6) \). Therefore, the wave-screen parameter can be used for efficient design of upright perforated wave absorbers consisting of sheets of constant or variable porosities.

The results of this study also showed that \( \Gamma \) could be used for efficient design of upright perforated wave filters. Thus, it was concluded that this parameter was the most important parameter to determine the hydraulic performance of single perforated sheets, and upright perforated wave filters and absorbers.

5. Conclusions

The results of two sets of experimental studies were presented for the measurements of the transmission coefficients of waves through single perforated sheets and upright perforated wave filters composed of 2 and 4 screens. The experiments illustrated that:

i) Transmission coefficient increased with increasing wave period and screen porosity and it decreased with increasing wave steepness.

ii) The spacing between perforated plates did not have an important effect on the transmission coefficients.

iii) The transmission coefficient decreased as the number of perforated sheets increased.

iv) The transmission coefficient through single perforated sheets or upright perforated wave filters could be determined as a function of the wave-screen parameter and the number of sheets. This coefficient increased with increasing the wave-screen parameter.

Moreover, employing the data of wave transmission coefficients gathered from different sources, it was noted that these coefficients were calculable simply by using equation (3).

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