韓國海岸 · 海洋工學發表論文集 (2003)
第14分, pp. 103-109

A Screen Wave Absorber System in a Wave Flume
파랑 수조에서의 파랑흡수를 위한 다중 스크린 시스템

Jung Lyul Lee[1]
이정렬[1]

1. Introduction

Wave flumes are usually equipped with a wave generator at one end and a wave absorber at the other end. The absorbers could be broadly classified into two main categories: active and passive wave absorbers. A typical passive wave absorber to eliminate unwanted reflections is the beach of constant or varying slopes reaching the bottom. However, such the absorber occupies a significant part of a wave tank and is not sufficiently effective to prevent reflective waves in a certain level. For these reasons, other types of wave absorbers of more or less complex shapes are used. In this study, a screen wave absorber system made of vertical perforated plates is examined so that theoretical efficiency minimizing reflected energy is given in several terms such as spacing between screens. The screen absorber uses porosity as a means to destroy wave energyand its damping mechanism is based on the fact that the reflection is smaller when the resonance is excited so that more energy dissipates through porosity. A primary merit of screen absorbers is that dissipation can be controlled varying the space between sheets and varying the diameter of the wires of the screen webbing.

The absorption of wave energy in a wave flume has drawn considerable attention of many researchers over the years and the studies have been mainly conducted on a theoretical or experimental basis. The earliest work on the screen assembly was done by Goda and Ippen (1963), and also later by Keulegan (1968, 1973). However, the reflections from wave absorbers were approximately analyzed. For a single permeable thin structure, Macaskill (1979) and Chwang (1983) provided more sophisticate description using the full inviscid linearised theories. Soon after, a number of authors have also considered the problems of two or more permeable thin screens. For single and double slotted breakwaters, Hagiwara (1984) proposed a theoretical analysis using an integral equation derived for the unknown horizontal velocity components in a pervious wall, Twu and Lin (1991) and Losada et al. (1993) developed analytical solutions for a wave absorber containing a number of thin screens by the using orthogonality property.

In this study, a theoretical approach is applied to design an absorbing system of screen sheet type (As an example, see Fig. 1) that produces the least amount of wave reflection when it is struck by a known incident waves. The method is simply derived under the crucial relation for a vertical thin screen without the use of orthogonality property. In Section 2, it is shown that the problem of upright screen absorbers or porous breakwaters can be given by plane wave solution. The main concept and resulting matrix equation is given in Section 3. The solution is compared with the measured data of Twu and Lin (1991).

성균관대학교 토목환경공학과 (Corresponding Author : Jung L. Lee, Department of Civil and Environmental Engineering, Sungkyunkwan University, Chunchun-Dong, Jangan-Ku, Suwon, 440-746, Korea, jllee@skku.edu)

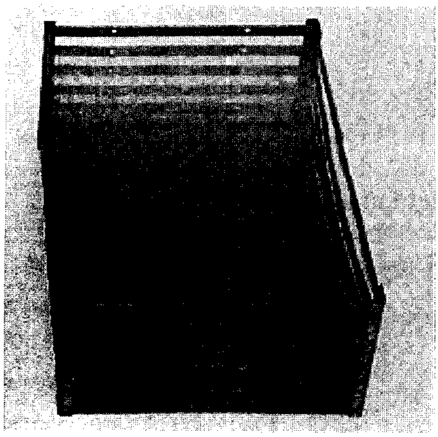

Fig. 1. Wire mesh screen (Keulegan, 1973).

2. A single screen problem

We shall first consider the wave motions against a vertical porous screen. Wave motions are assumed to be uniform in the longitudinal direction thus allowing vertically two-dimensional analysis. It is also assumed that wave motions are small so that linear theory is applicable. For analysis, the Cartesian coordinate system with the origin on the mean free surface and the z-axis positive upward is used. An incident waves normally propagate in the positive x-direction toward a screen which is situated at x=0 in water of constant depth h. Assuming that the fluid is invicid and incompressible and its motion irrotational, the velocity potential can be written as $\Phi(x, y, z, t) = Re[\phi(x, z) exp(-i\sigma t)]$ with harmonic motion of frequency σ , where $i = \sqrt{-1}$. Then $\phi(x, z)$ satisfies the Laplace equation

$$\nabla^2\phi = 0, \quad -h < z < 0 \tag{1}$$

and the following linearized boundary conditions :

$$-\sigma^2\phi + g\frac{\partial\phi}{\partial z} = 0, \quad z = 0 \tag{2a}$$

$$\frac{\partial\phi}{\partial z} = 0, \quad z = -h \tag{2b}$$

where g and h are the gravitational acceleration and water depth, respectively. The boundary condition along the porous screen may be developed on the basis of the formulation of Sollitt and Cross (1972) and as adopted by Yu (1995) for a thin vertical porous breakwater extending to the seabed. This may be expressed at $x=0$ for $-h \leq z \leq 0$ as

$$\frac{\partial\phi}{\partial x} = -ikG(\phi_2 - \phi_1) \tag{3}$$

where G is a porous-effect parameter which is generally complex. Eq. (3) corresponds to the fluid velocity normal to the screen being proportional to the pressure difference across the screen, with a complex constant of proportionality. In the present study, the method of Sollitt and Cross (1972) is followed and G expressed by

$$G = \frac{\epsilon(f + is)}{kb(f^2 + s^2)} \tag{4}$$

where ϵ is the porosity of the screen , f is the friction coefficient, b is the screen thickness, k is the wave number determined by the dispersion relationship and s is the inertia coefficient given by

$$s = 1 + C_m\left(\frac{1-\epsilon}{\epsilon}\right) \tag{5}$$

In Eq. (5), C_m is the added mass coefficient. For a porous medium, s has a value of unit while the friction coefficient f has been considered to be independent of the flow and is associated with the porous structure. Therefore, the real part of G corresponds to the resistance of the screen and the imaginary part of G corresponds to the phase differences between the velocity and the pressure because of inertial effects.

Yu (1995) obtained the following solutions which have the correct behavior as $x \rightarrow \pm\infty$ and satisfy the porous boundary conditions:

$$\phi = A_o f(z)\left(e^{ikx} + \frac{1}{1+2G}e^{-ikx}\right) \quad x < 0 \tag{6a}$$

$$\phi = A_o f(z)\frac{2G}{1+2G}e^{ikx} \quad x > 0 \tag{6b}$$

where, A_o is the magnitude of incident wave potential given as

$$A_o = \frac{gH_o}{2\sigma} \tag{7}$$

and from linear wave theory,

$$f(z) = \frac{coshk(h+z)}{coshkh} \tag{8}$$

Equations (6a) and (6b) imply that the evanescent eigenmodes are not necessary to satisfy the matching conditions. It was assumed that the porous screen has a homogeneous and very fine porosity. The reflection and transmission coefficients of complex value, r and t, can be easily determined from Eqs. (6a) and (6b), respectively as

$$r = \frac{1}{1+2G} \quad \text{and} \quad t = \frac{2G}{1+2G} \tag{9}$$

Then the energy-loss coefficient is obtained as

$$e = \frac{4G_r}{(1+2G_r)^2 + (2G_i)^2} \tag{10}$$

where G_r is the real part of G and G_i is the imaginary part of G. In the case that the resistance effect dominates the inertial one and thus G is considered as a real value, therefore, the energy dissipation coefficient can be expressed as Kriebel (1992)'s formula:

$$e = 2t(1-t) \tag{11}$$

3. A multiple scattering problem

Here we consider the case in which the propagating effects dominate all other hydrodynamic effects. Then we obtain the following equations as a resultant of incident and scattering waves:

$$\psi^-(x) = A_-e^{ik}x^x + B_-e^{-ik}x^x, \quad x < 0 \tag{12a}$$

$$\psi^+(x) = A_+e^{ik}x^x + B_+e^{-ik}x^x, \quad x > 0 \tag{12b}$$

where ψ is the velocity potential of the propagating mode defined at the free surface, A_- and B_+ correspond to the incoming waves from the left and the right, respectively, and A_+ and B_- correspond to the scattering waves toward the right and the left from $x = 0$ where the screen is located, respectively. Now we seek the overall potentials for waves incident upon the screen from either the left or the right. The linear superposition gives

$$\psi^-(x) = A_-e^{ik}x^x + B_+te^{-ik}x^x + A_-re^{-ik}x^x, \quad x < 0 \tag{13a}$$

$$\psi^+(x) = B_+e^{ik}x^x + A_-te^{-ik}x^x + B_+re^{-ik}x^x, \quad x > 0 \tag{13b}$$

where t is the *transmission coefficient* and r is the reflection coefficient. Transmission coefficient of complex value t is given as $1-r$ for the thin vertical screen. Note that ψ_x is continuous although ψ jumps across a screen. Comparing Eq. (12) with Eq. (13) yields.

$$A_+ = tA_- + rB_+ \quad \text{and} \quad B_- = rA_- + tB_+ \tag{14}$$

Equation (14) can be obtained by using Jost functions. Rearranging Eq. (13) with use of $r+t=1$ gives

$$\psi^-(x) = A_-e^{ik}x^x + B_-te^{-ik}x^x + r(A_- - B_+)e^{-ik}x^x, \quad x < 0 \tag{15a}$$

$$\psi^+(x) = A_-e^{ik}x^x + B_-te^{-ik}x^x - r(A_- - B_+)e^{ik}x^x, \quad x > 0 \tag{15b}$$

Thus the combined scattering constant R becomes $r(A_- - B_+)$. The first two terms are incident wave terms, while the last term is the so-called scattering term. Then, it is noticeable that the scattering constant can be expressed in terms of the gradient of velocity potential, $\nabla\psi$, across a screen:

$$R = \frac{\alpha}{ik}\frac{\partial\psi}{\partial x}(0) \tag{16}$$

where α is defined as rt^{-1}.

Now we consider the two porous screen problem in which two screens occupy $x = \pm b$. We obtain the following equations with two scattering terms in which screens are posed:

$$\psi^{(I)} = e^{ikx} + R_1 e^{-ik(x+b)} + R_2 e^{-ik(x-b)} \quad x \leq -b \tag{17a}$$

$$\psi^{(II)} = e^{ikx} - R_1 e^{ik(x+b)} + R_2 e^{-ik(x-b)} \quad -b \leq x \leq b \tag{17b}$$

$$\psi^{(III)} = e^{ikx} - R_1 e^{ik(x+b)} - R_2 e^{ik(x-b)} \quad x \geq b \tag{17c}$$

Applying Eq. (16) at $x = -b$, we obtain the scattering complex constant at the first screen R_1

$$R_1 = \alpha_1 (e^{-ikb} - R_1 - R_2 e^{2ikb}) \tag{18}$$

where $\alpha_1 = \frac{r_1}{t_1}$

Similarly we obtain the scattering constant at the second screen R_2

$$R_2 = \alpha_2 (e^{ikb} - R_1 e^{2ikb} - R_2) \tag{19}$$

where $\alpha_2 = \frac{r_2}{t_2}$

Then, the scattering constants R_1 and R_2 can be now found from two simultaneous equations as

$$R_1 = \frac{\alpha_1 [1 + \alpha_2 (1 - e^{4ikb})] e^{-ikb}}{(1+\alpha_1)(1+\alpha_2) - \alpha_1 \alpha_2 e^{4ikb}} \tag{20a}$$

$$R_1 = \frac{\alpha_2 e^{ikb}}{(1+\alpha_1)(1+\alpha_2) - \alpha_1 \alpha_2 e^{4ikb}} \tag{20b}$$

If we substitute (20a) and (20b) to (17a), (17b) and (17c), we now obtain the waves at corresponding regions. Here we represent the reflection and transmission complex coefficients given as

$$R \sim \frac{\alpha_1 (1+\alpha_2) + \alpha_2 (1-\alpha_1) e^{4ikb}}{(1+\alpha_1)(1+\alpha_2) - \alpha_1 \alpha_2 e^{4ikb}} \tag{21a}$$

$$T \sim \frac{1}{(1+\alpha_1)(1+\alpha_2) - \alpha_1 \alpha_2 e^{4ikb}} \tag{21b}$$

These can be written in terms of the reflection coefficient r and transmission coefficient t for a single screen as follows.

$$R \sim \frac{r_1 + r_2 (t_1 - r_1) e^{4ikb}}{1 - r_1 r_2 e^{4ikb}} \tag{22a}$$

$$T \sim \frac{t_1 t_2}{1 - r_1 r_2 e^{4ikb}} \tag{22b}$$

Now consider an array of vertical screens dividing the water into $N+1$ regions. Then for N screens with arbitrary length a and location l, we have $N+1$ descriptions of propagating velocity potential components:

$$\psi^m = e^{ikx} - \sum_{n=1}^{N} S_n^m R_n e^{S_n^m ik(x-l_n)} \Omega_m \tag{23}$$

where

$$S_n^m = -1 \text{ for } m \leq n, \; S_n^m = 1 \text{ for } m > n$$

The equation for the mth scattering constant is as follows.

$$R_m = \alpha_m (e^{ikl_m} - \sum_{n=1}^{N} R_n e^{ik|l_n - l_m|}) \tag{24}$$

This constructs the $N \times N$ matrix equation of the form

$$\begin{bmatrix} 1+\alpha_1 & \alpha_1 e^{ik(l_2-l_1)} & \alpha_1 e^{ik(l_3-l_1)} & \cdots & \alpha_1 e^{ik(l_N-l_1)} \\ \alpha_2 e^{ik(l_2-l_1)} & 1+\alpha_2 & \alpha_2 e^{ik(l_3-l_2)} & \cdots & \alpha_2 e^{ik(l_N-l_1)} \\ \alpha_3 e^{ik(l_3-l_1)} & \alpha_3 e^{ik(l_3-l_2)} & 1+\alpha_3 & \cdots & \alpha_3 e^{ik(l_N-l_3)} \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ \alpha_N e^{ik(l_N-l_1)} & \alpha_N e^{ik(l_N-l_2)} & \alpha_N e^{ik(l_N-l_3)} & \cdots & 1+\alpha_N \end{bmatrix} \begin{bmatrix} R_1 \\ R_2 \\ R_3 \\ \vdots \\ R_N \end{bmatrix} = - \begin{bmatrix} \alpha_1 e^{ikl_1} \\ \alpha_2 e^{ikl_2} \\ \alpha_3 e^{ikl_3} \\ \vdots \\ \alpha_N e^{ikl_N} \end{bmatrix} \tag{25}$$

Once the unknown complex constants are determined, the reflection and transmission coefficients can be calculated as

$$R = \sum_{n=1}^{N} R_n e^{ikl_n} \quad (26a)$$

$$T = 1 - \sum_{n=1}^{N} R_n e^{-ikl_n} \quad (26b)$$

For the three screens of equal length and spacing as an example, we can obtain three unknowns, R_1, R_2 and R_3, by using Cramer's rule as

$$R_1 = \frac{\alpha_1}{\Delta}[(1+\alpha_2)(1+\alpha_3) - (1-\alpha_2)\alpha_3(e^{2ik(l_3-l_1)} - e^{2ik(l_3-l_2)} - e^{2ik(l_2-l_1)})] \quad (27a)$$

$$R_2 = \frac{\alpha_2 e^{ik(l_2-l_1)}}{\Delta}[(1+\alpha_3) + \alpha_1\alpha_3(e^{ik(l_3-2l_1)} + e^{ik(2l_3-2l_2-l_1)} - e^{2ik(l_3-l_2)}) - \alpha_3 e^{2ik(l_3-l_2)}] \quad (27b)$$

$$R_3 = \frac{\alpha_3 e^{ik(l_3-l_1)}}{\Delta} \quad (27c)$$

where Δ is the determinant given as

$$\Delta = (1+\alpha_1)(1+\alpha_2)(1+\alpha_3) + \alpha_1\alpha_2\alpha_3 e^{2ik(l_3-l_1)} - (1+\alpha_1)\alpha_2\alpha_3 e^{2ik(l_3-l_2)} - \alpha_1\alpha_3 e^{2ik(l_3-l_1)} - \alpha_1\alpha_2(1+\alpha_3)e^{2ik(l_2-l_1)} \quad (28)$$

Then the reflection and transmission complex coefficients are obtained as

$$R \sim \frac{1}{\Delta}[R_1 + R_2 e^{-ik(l_1-l_2)} + R_3 e^{-ik(l_1-l_3)}] \quad (29a)$$

$$T \sim 1 - \frac{1}{\Delta}[R_1 + R_2 e^{ik(l_1-l_2)} + R_3 e^{ik(l_1-l_3)}] \quad (29b)$$

These coefficients can be written in terms of the reflection coefficient for a single screen r as

$$R \sim \frac{1}{\Delta}[\alpha_1(1+\alpha_2)(1+\alpha_3) + (1-\alpha_1)(1-\alpha_2)\alpha_3 e^{2ik(l_3-l_1)} + (1-\alpha_1)\alpha_2(1+\alpha_3)e^{2ik(l_2-l_1)} - \alpha_1\alpha_2\alpha_3 e^{2ik(l_3-l_2)}] \quad (30a)$$

$$T \sim \frac{1}{\Delta} \quad (30b)$$

Note that T is always given as the inverse of determinant irrespective of the number of screens. These coefficients can be written in terms of r and t as

$$R \sim \frac{1}{\Delta_1}[r_1 + (t_1 - r_1)(t_2 - r_2)r_3 e^{2ik(l_3-l_1)} + (t_1 - r_1)r_2 e^{2ik(l_2-l_1)} - r_1 r_2 r_3 e^{2ik(l_3-l_2)}] \quad (31a)$$

$$T \sim \frac{t_1 t_2 t_3}{\Delta_1} \quad (31b)$$

where Δ_1 of (31) is given by

$$\Delta_1 = 1 + 2r_1 r_2 r_3 e^{2ik(l_3-l_1)} - r_1 r_2 e^{2ik(l_2-l_1)} - r_2 r_3 e^{2ik(l_3-l_2)} - r_1 r_3 e^{2ik(l_3-l_1)} \quad (32)$$

4. Results

The present method described above is now validated by comparison with experiments carried out by Twu and Lin (1991). Figs. 2-5 show comparisons of reflection coefficient with experiments of Twu and Lin (1991) for one, two and three porous plates limited with the impermeable back wall. In the experiments, a water depth, h=0.5m and the non-dimensional spacing parameter, l/h=0.88 were adopted while in the present calculation the other parameters, b=0.024, ε =0.58 and s=1 are adopted based on Losada et al. (1993). For the single plate, Eq. (22a) is used to obtain the reflection coefficients with r_2=1 and t_2=0 for an impermeable wall. Similarly, for the two plate, Eq. (31a) is used with r_3=1 and t_3=0 for an impermeable wall. The reflection and transmission coefficients of a single screen which are required in Eqs. (22a) and (31a) are obtained from Eq. (9). The calculated results shown in Figs. 2 and 3 were obtained by using with f=0.6. With the friction coefficient constant, the agreement for two-plates becomes worse at high frequency. Since the friction may depend on flow strength, the linearly decreasing friction coefficients from 7 to 3.25 are used with increasing frequency of the shown range to get similar agreement for single plate as shown in Fig. 4 and closer agreement for two plates as shown in Fig. 5. However, the further study is required to recognize the clear role of friction coefficients.

5. Conclusions

In this study, a theoretical method is present for the design of an absorbing system made of wire-webbed screen assembly so that the system produces the least amount of wave reflection when it is struck by a known incident waves. The method is simply derived under the crucial relation for a vertical thin screen without the use of orthogonality property and the reflection is simply obtained by solving a matrix equation of $N^{\times}N$ where N is the number of water zones divided by screens. The present method was verified through comparison with measured data of Twu and Lin (1991).

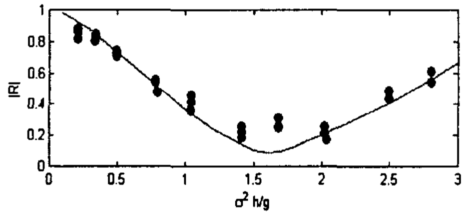

Fig. 2. Theoretical reflection coefficients compared with experimental data by Twu and Lin(1991) for a single-porous-plate wave absorber with the back wall.

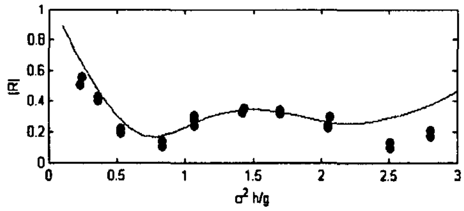

Fig. 3. Theoretical reflection coefficients compared with experimental data by Twu and Lin(1991) for a two-porous-plate wave absorber with the back wall.

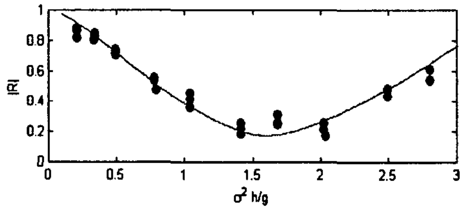

Fig. 4. Theoretical reflection coefficients (for varying friction factor) compared with experimental data by Twu and Lin(1991) for a single-porous-plate wave absorber with the back wall.

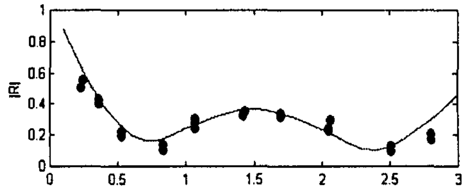

Fig. 5. Theoretical reflection coefficients (for varying friction factor) compared with experimental data by Twu and Lin (1991) for a two-porous-plate wave absorber with the back wall.

References

Chwang, A.T., 1983. A porous-wavemaker theory. *J. Fluid Mech.*, 132p, pp. 395-406.

Goda, Y. and Ippen, A.T., 1963. Theoretical and experimental investigation of wave energy dissipators composed of wire mesh screen.Report No. 60, Massachusetts Institute of Technology, Hydrodynamics Laboratory, Cambridge, Mass.

Hagiwara, K., 1984. Analysis of upright structure for wave dissipation using integral equation. *Proc. 19th Coast. Engrg. Conf.*, Vol. 3, ASCE, New York, pp. 1810-1826.

Isaacson, M., Baldwin, J., Premasiri, S. and Yang, G., 1993. Wave interaction with double slotted barriers. *Appl. Oc. Res.*, 21p, pp 81-91.

Keulegan, G.H., 1968. Wave damping effects of screen; hydraulic model investigation. Report No. 2-12, U.S. Army Engineer Waterways Experiment Station, CE, Vicksburg, Miss.

Keulegan, G.H., 1973. Reflection characteristics of screen wave absorbers. Research Report H-73-3, U.S. Army Engineer Waterways Experiment Station, HL, Vicksburg, Miss.

Kriebel, D.L., 1992. Vertical wave barriers: wave transmission and wave forces. *Proc.23rd Coast. Engrg. Conf.*, ASCE, New York, pp. 1313-1326.

Losada, I.J., Losada, M.A. and Baquerizo, A., 1993. An analytical method to evaluate the efficiency of porous screens as wave dampers. *Appl. Oc. Res.*, 15, 207-215.

Macaskill, C., 1979. Reflextion of water waves by a permeable barrier. *J. Fluid Mech.*, 95p, pp. 141-157.

Mei, C.C., 1983. *The Applied Dynamics of Ocean Surface Waves.* Wiley, New York.

Sollitt, C.K. and Cross, R.H., 1972. Wave transmission through permeable breakwaters. *Proc. 13th Coast. Engrg. Conf.*, Vol. 3, ASCE, New York, pp. 1827-1846.

Twu, S.W. and Lin, D.T., 1991. On a highly effective wave absorber. *Coastal Engrg.*, 15, pp. 389-405.

Yu, X.-P., 1995. Diffraction of water waves by porous breakwaters. *J. Wtrwy., Port, Coast., and Oc. Engrg.*, ASCE, 121(6), pp.275-282.