An Analytical and Experimental Study of Progressive Linear Waves Interacting with Thin Porous Media

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Abstract

This is a combined analytical and experimental investigation on the interaction of progressive linear water waves passing through a porous wall. The analytical solutions in terms of the velocity potentials and free-surface elevations are derived by following the linear wave theory with the application of the Darcy’s law based porous wall boundary condition. The effect of porous parameter on the reflection and transmission coefficients and associated energy losses is analyzed. The experimental study was carried out in a 41.5-ft long, 1-ft wide wave flume with waves generated by a piston type wavemaler. In the tests, the porous walls used were thin steel circularly perforated screens with specific pore sizes and porosities. A series of incident and transmitted wave heights were recorded and analyzed to get the transmission coefficients and the energy loss of waves due to their interactions with given porous walls. Use of the measured data, the material constants of various porous walls can be experimentally determined. The analytical transmission coefficients with the inputs of calibrated material constants are found to agree reasonably well with measured data obtained for validation.

Introduction

Porous media are commonly used in many fluid applications to remove the solids flowing in a fluid. This includes, but is not limited to hydroelectric power plant water intakes, water pump intakes, and wastewater treatment plants. Another application of porous media in the fluid domain is the dissipation of wave energy due to the wave passing through the porous structure. This paper will focus on the latter application of porous media.
The application of porous structures in coastal areas to dissipate wave energy is an important safety measure for floating structures along with protecting seawalls. The porous media dissipate wave energy due to the frictional forces applied to the wave energy as it passes through the porous material. It also dissipates energy due to the turbulence created around the porous structure. The solid portions of the porous structure reflect some of the wave energy to decrease the transmitted wave energy as well.

The applications of porous media to dissipate wave energy are vast. The most common is in coastal areas where the porous media (like a porous wall) is placed in front of seawalls to decrease the force of the waves on the seawall thereby requiring less structural strength in the wall and giving a greater service life due to the decreased forces. This same idea can be applied to offshore structures as well. For example, the support columns of an offshore oil platform can be surrounded by porous media and thereby either decreasing the necessary column size or increasing the structures ability to withstand large waves. Porous media may be of use to dissipate waves around floating structures to increase the stability of the floating structures. The porous structures may also be used around harbors to provide calmer seas and safer shipping inside the harbor even when the seas outside the harbor are rough. Porous media can be a very valuable tool in proving for safety in coastal areas. The studies of waves generated by porous wavemaker and interaction of linear waves with porous structures for controlling of the reflected and transmitted waves have been carried out by Chwang (1983), Chwang and Li (1983), Chwang and Wu (1994), Wang and Ren (1993, 1994), Hu and Wang (2005), and others. A review article for interaction between wave motion and porous media was given by Chwang and Chan (1998).

This study performs a combined analytical and experimental investigation on the interaction of linear water waves passing through a porous wall. The effect of porous
parameter as introduced by Chwang (1983) on the transmission and reflection coefficients is also examined. For obtaining the material constants of porous walls and the verification of the analytical solution, experimental measurements were carried out in a 1-ft wide, 41.5-ft long wave flume with waves generated by a piston-type wavemaker. Thin steel circularly perforated screens with specific pore sizes and porosities were used in the tests. Incident and transmitted wave heights for different wave and porous wall conditions were recorded and analyzed to get the transmission coefficients and the losses of wave energy. The measured data were used to determine the values of the material constant “b” of porous walls defined in the analytical derivations. This material constant is theorized to have a relationship with the porosity, pore size, and screen material and is given in a unit of length. The experimentally determined material constants are further used to compute the analytical transmission coefficients for the comparisons with experimental measurements.

Theoretical Solutions

The theoretical background for this study is based on the linear wave theory with porous wall boundary condition proposed by Chwang and Li (1983). Waves are assumed to propagate from right to left in an infinitely long channel. The definitition sketch of the problem, including fluid domain, variables, and the coordinate system is shown in Fig. 1. Also note all variables presented in this paper are defined in Attachment 1.
From Fig. 1, it can be noted the velocity potential in region 1, $\Phi_i$, includes the incident velocity potential $\Phi_I$ and the reflected velocity potential $\Phi_R$, i.e. $\Phi_i = \Phi_I + \Phi_R$, whereas the velocity potential in region 2, $\Phi_2$, is represented by the transmitted velocity potential $\Phi_T$, having $\Phi_2 = \Phi_T$. $\Phi_1$ and $\Phi_2$ are found to satisfy the Laplace equation

$$\nabla^2 \Phi = \frac{\partial^2 \Phi_i}{\partial x^2} + \frac{\partial^2 \Phi_i}{\partial z^2} = 0 \quad i = 1, 2 \tag{1}$$

and the following boundary conditions

$$\frac{\partial \Phi_i}{\partial z} = 0 \quad \text{at} \ z = -h \quad i = 1, 2 \tag{2}$$

$$\frac{\partial \Phi_i}{\partial z} = \frac{\partial \eta_i}{\partial t} \quad \text{at} \ z = 0 \quad i = 1, 2 \tag{3}$$

$$\frac{\partial \Phi_i}{\partial t} + g \eta_i = 0 \quad \text{at} \ z = 0 \quad i = 1, 2 \tag{4}$$
The incident velocity potential $\Phi_I$ has the form of

\[
\Phi_I = a g \frac{\cosh[k(z + h)]e^{i(kx + \omega t)}}{\omega \cosh(kh)}
\]  

(5)

where $a$ is the incident wave amplitude, $g$ is the gravitational constant, $\omega$ is the wave frequency, and $k$ denotes the wave number. The wave number $k$ and the frequency $\omega$ satisfy the usual dispersion equation

\[
\omega^2 = g k \tanh(kh).
\]  

(6)

For the study of linear waves propagating past a porous wall, a porous wall boundary condition needs to be included in the analytical analysis. The wall boundary condition can be expressed as

\[
\frac{\partial \Phi_1}{\partial x} = \frac{\partial \Phi_2}{\partial x} = u(z, t) \quad \text{at} \ x = 0
\]  

(7)

where, $u(z, t)$ is the fluid velocity flows through the porous wall. Applying the Darcy’s law (Chwang, 1983), we have

\[
u(z, t) = \frac{b}{\mu} [p_2 - p_1]
\]  

(8)

and

\[
\frac{\partial \Phi_1}{\partial x} = \frac{\partial \Phi_2}{\partial x} = \frac{b}{\mu} \left[ \rho \frac{\partial \Phi_1}{\partial t} - \rho \frac{\partial \Phi_2}{\partial t} \right]
\]  

(9)

where $b$ is the material constant with dimension of length and $\mu$ is the dynamic viscosity of the fluid.

The solutions of $\Phi_R$ and $\Phi_T$, including the propagating mode and the evanescent mode, can be derived by solving Eq. (1) with the application of the boundary conditions.
(2), (3), (4), and (8b). However, the coefficients for the solutions of the evanescent modes are found to be zero. The solutions for $\Phi_R$ and $\Phi_T$ are derived as
\begin{equation}
\Phi_R = R \frac{ag \cosh(k(z+h))e^{i(kx-\omega t)}}{\omega \cosh(kh)}
\end{equation}
and
\begin{equation}
\Phi_T = \Phi_2 = T \frac{ag \cosh(k(z+h))e^{i(kx+\omega t)}}{\omega \cosh(kh)}
\end{equation}
with the reflection coefficient $R$ and transmission coefficient $T$ determined as
\begin{equation}
R = \frac{1}{2G_0 + 1}
\end{equation}
\begin{equation}
T = \frac{2G_0}{2G_0 + 1}.
\end{equation}
As defined below, $G_0$ is the dimensionless porous-effect parameter introduced by Chwang and Li (1983)
\begin{equation}
G_0 = \frac{\rho \omega b}{\mu k}
\end{equation}
It should be noted $R^2 + T^2 \neq 1$ and $R^2 + T^2 < 1$, indicating part of the wave energy is dissipated in the process of waves propagating past a porous wall.

The solution for $\Phi_1$ can then be expressed as
\begin{equation}
\Phi_1 = \frac{ag \cosh(k(z+h))e^{i(kx-\omega t)}}{\omega \cosh(kh)} + R \frac{ag \cosh(k(z+h))e^{i(kx+\omega t)}}{\omega \cosh(kh)}
\end{equation}
Introducing the Reynolds number, $Re = \rho b \sqrt{gh} / \mu, G_0$ can be related to the Reynolds number as.
\[ G_0 = \text{Re} \left( \frac{\tanh(kh)}{kh} \right) . \]  

Substituting Eqs. (15) and (11), respectively, into Eq. (4), we have the formulations of the free-surface elevation for region 1 and region 2 as

\[ \eta_1 = a \sin(\omega t) + \frac{1}{2G_0 + 1} a \sin(kx - \omega t) \]  

\[ \eta_2 = \frac{2G_0}{2G_0 + 1} a \sin(kx + \omega t) \]

### Experimental Study

**Equipment**

All experiments for this research were conducted in the University of Houston’s Hydraulic Lab. Within the lab a 41.5-feet long, 1-foot wide, and 3-feet deep glass walled rectangular flume (Fig. 2-(a)) was converted from its typical use for open channel flow into a closed end wave tank for the experimentation. This was accomplished by sealing the open end with a steel plate and foam caulking (Fig. 2-(c)).

![Figure 2- (a) Flume tank (b) End tank (c) Newly sealed end](image_url)
The wavemaker and mounting frame (Fig. 3) for the experiments were uniquely manufactured for this new wave tank facility. The wavemaker used was a piston type wavemaker. It is governed by the wavemaker theory presented in Equation (19). This theory shows that the change in paddle stroke only corresponds to a change in wave amplitude.

\[
\frac{a}{S} = \frac{2 \cosh(2kh - 1)}{\sinh(2kh) + 2kh}
\]  

(19)

The wavemaker used consists of a motor that is computer controlled by a motion amplifier. This computer controlled amplifier was used to create repeatable uniform linear progressive sinusoidal waves. The Amplifier used was a Xenus Panel XTL-230-40 Amplifier and controlled by the Copley Motion Explorer CME 2 program. Attached to the motor is a horizontal plate mounted with a vertical galvanized metal paddle as a wavemaker (Fig. 3-(c)). The paddle is also coated on the edges with a rounded plastic to create a better seal with the sides of the tank. On the back side of the paddle near the still water depth foam tape was added to add to the seal around the paddle. This entire assembly is mounted onto a moving frame (Fig. 3-(a)). This frame has an electric winch attached to the top of the wavemaker system in order to raise and lower the wavemaker into and out of the tank. The mounting frame was bolted to the top of the existing flume. The mounted assembly can be seen below.
To dissipate unwanted reflected waves in the tank in order to simulate an infinitely long channel various screens and bags of gravel were added at either end of the tank. In the area behind the wavemaker, first a nylon mesh bag of gravel was added that was encased in a plastic mesh and placed against the sealed wall (Figure 4-(c)). In front of that a stepped metal mesh screen was placed at an angle so that it rested on the back gravel (Figure 4-(b)). Between the stepped metal mesh screen and the wavemaker paddle another nylon mesh bag of gravel encased in plastic mesh was added to further reduce wavemaker induced wave oscillation (Figure 4-(a)).
To dissipate waves that have already been recorded and to prevent them from reflecting off of the back wall of the end tank more bags of gravel and screens were added. At the back wall two nylon mesh bags of gravel were wrapped in the plastic mesh and stacked on top of each other (Fig. 5-(d)). In front of the gravel there are approximately 8 feet of plastic crates stacked on top of and beside each other (Fig. 5-(c)). On the wave side of the stacks of crates the plastic mesh was rolled into three cylinders approximately 4 inches in diameter and attached to the crates (Fig. 5-(b)). In front of the rolled mesh four nylon mesh bags of gravel were placed inside of four more plastic crates. These were arranged with two crates at either side of the tank against the cylindrical meshes and the other two at the center of the tank touching each other (Fig. 5-(a)). Examples of the energy absorbers at the end of the tank can be seen below.

Figure 5- (a) Crated gravel (b) Rolled Mesh (c) Plastic crates (d) Rolled mesh with gravel.
In order to measure the wave heights for the experiment wave gages were required. These gages were first calibrated in standing still water in order to obtain accurate results. The wave gage system used are RBR WG-50 boxes (Fig. 6-(a)) and attached probes (Fig. 6-(b)). These gages measure the water depth by reporting the voltage and range from -5 volts to 5 volts. This voltage was measured and recorded using a National Instruments NI USB-6009 analog input USB port and the accompanying Signal Express computer program to record the numeric results.

![Wave gage box](image1.png) ![Mounted gage probe](image2.png) ![USB voltage converter](image3.png)

Figure 6- (a) Wave gage box (b) mounted gage probe (c) USB voltage converter

Once calibrated, these gages were placed in the tank 64.25 inches apart. Care was also taken to place the gages as near to the center or “Zero” mark as possible. They were mounted to the tank frame (Fig. 7) for stability and not moved from their locations on the tank during the testing. When sampling the gages recorded the wave height at a sampling rate of 20 Hz or 20 samples per second. The upstream gage was placed 129.5 inches from the wavemaker with the second gage the additional 64.25 inches away. When the porous media was added to the wave tank it was placed between the gages 20.5 inches upstream and 43.75 inches downstream of the porous structure. The downstream gage was placed further from the porous structure than upstream gage so that only the transmitted wave was recorded and not the turbulence and evanescent waves around the structure were recorded. An example of the mounted gages can be seen here.
The porous media used for the experiments were thin flat vertical screens. There were eight screens tested under two different wave conditions. These screens were 11 gage galvanized steel plates cut with a round-60° staggered center hole pattern (Fig. 8). This pattern allowed Equation (20) as seen below to be used to calculate the open area percentage or porosity,

$$OA\% = \frac{90.69 \times D^2}{C^2}$$

(20)

where D is hole diameter and C is center of hole to center of hole distance. Figure 8 gives a detailed image of the locations of the D and C values.

Figure 8- Location of D and C for a rounded -60° staggered center screen pattern.
There were four screens with 0.125 inch pore sizes and four screens with 0.25 inch pore sizes (Fig. 9). Each set of screens has four porosities that are equal to the other set. They are 40.31%, 29.61%, 22.67%, and 16.08%. Exact screen specifications can be found in Attachment 2 along with photographs of each screen. Each screen is approximately 1 foot wide by 4 feet tall and has a foam tape on the sides in order to get a better seal with the sides of the tank. Each screen was placed vertically in the tank and was made square in the tank using a carpenter’s square (Figs. 10-(a) to 10-(c)). This was done in order to ensure waves are normally incident upon the porous screen. During the test the carpenter’s square was clamped to the tank frame in order to ensure the screen remained in place during the testing.

(a)               (b)
Figure 9- (a) 0.125 in., 40.31% screen and (b) 0.25 in., 40.31% screen

**Experimental Methodology**

At the beginning of each testing session the depth of the still water in the tank was first measured. This was accomplished using a Pulsar acoustic depth gage (Fig. 11-(a)). This gage was attached to an Ultra 5 integration unit (Fig. 11-(b)) which calculated the depth of the water as compared to the gage’s known location above the bottom of the tank. Once the depth of the water was recorded the wavemaker was turned on to run
multiple incident waves in order to check the repeatability and form of the incident waves. This also allowed the motor to “warm up” as it was found that after the motor was not in use for a long period of time the initial waves were not as developed at the beginning of the first test as they would be at the beginning of the third or fourth as well as all subsequent tests.

![Figure 10](image1.png)

(a) Side view of screen in flume (b) front view of screen in flume (c) carpenter’s square mounting for screen

Once the repeatability and form of waves were checked three incident waves were recorded on both gages. Following this each screen would be placed in the water and three transmitted waves would be recorded. This procedure was followed to ensure accuracy of results and the true repeatability of the results. Between each wave test the

![Figure 11](image2.png)

(a) Pulsar acoustic depth gage (b) Ultra 5 unit
water was allowed to settle so that there was no wave interference from the previous test. This helped to ensure pure progressive linear waves were being tested and not the combination of progressive and reflected. Also, before each test the motor was “homed” to the exact same location so that all waves would originate from the same location and travel the same distance to the gages. The water depth set for the tests is 0.75 ft.

In each test, waves were recorded at both gages but the majority of the results presented in this study were based on the analyses using the data from the second or downstream gage in transmitted wave region as reflected waves are harder to separate from the combined wave profiles recorded in front of the porous screen. The incident waves (without the porous screen placed) were recorded at the same location as those measured for the transmitted waves under the condition with a porous screen to minimize the effect on the results due to the channel friction. The data were analyzed to obtain the incident and transmitted wave heights for each test case.

Results

The theoretical relationship between transmission coefficient $T$ and $G_0$ is shown in Fig. 12. It can be seen that as $G_0$ increases the transmission coefficient increases. From this result it can then be theorized that in order to decrease the energy of the transmitted wave through the porous medium the $G_0$ value should be minimized.
Figure 12- Effect of $G_0$ on transmitted wave.

The theoretical relationship of $T$ versus $kh$ is shown in Fig. 13. It can be seen that as $kh$ increases the $T$ decreases. Based on the definition of $kh$, the larger the $kh$ value reflects waves with shorter wave length. From Fig. 13, it can be concluded that thin porous medium is more effective at reducing energy for waves (or transmitted wave height) with relatively shorter wavelength waves as opposed to longer wavelength waves.

Figure 13- Effect of $kh$ on transmitted wave
The theoretical results for the reduction of the transmitted waves for the same incident wave \((a = 1 \text{ ft})\) with changes in \(G_0\) can be seen in Fig. 14. This figure shows the wave surface profile of the combined incident and reflected wave to the right of \(x = 0\) and the transmitted wave surface profile to the left. The incident wave travels from right to left as indicated by the arrow. As stated above as \(G_0\) decreases, so does the transmitted wave. This relation is somewhat different for the reflected waves upstream of the porous medium. As \(G_0\) decreases the combined reflected and incident wave also increases due to the increased amount of energy reflected by the porous medium when \(G_0\) decreases. In real applications this would lead to a more turbulent upstream area in exchange for a calmer downstream.

![Wave Interaction with Porous Medium](image)

Figure 14- Reflected and Transmitted wave profiles with changing \(G_0\)

The reduction of wave energy can also be modeled by squaring the T and R coefficients. This is done because wave energy is the square of amplitude so the square
of R and T is respectively the energy ratio of reflected and transmitted waves to the incident waves. These squared values are represented by $CT = T^2$ and $CR = R^2$ for transmitted waves and reflected waves, respectively. For a wave system without energy losses, $CT + CR$ should be equal to 1. Figure 15 presents $CT$, $CT$, or $CR + CT$ versus $G_0$ to show the variation of wave energy for waves propagating past a porous wall. When $G_0$ equals to 0, $CT$ is zero and $CR$ is 1. As expected, the case with $G_0 = 0$ represents waves encountering a solid barrier. Therefore, there is no transmitted wave. For another limiting consideration, as $G_0$ becomes very large $CT$ approaches one and $CR$ approaches zero. The interesting part of the $CR$ and $CT$ relationship occurs between these limiting points. Due to part of energy dissipated through the process of a wave passing through a porous medium at moderate $G_0$ values, $CR$ and $CT$ do not sum to one. The results shown in Fig. 15 lead to a conclusion that at $G_0 = 0.5$ wave energy dissipation is at a maximum. From this it can be seen that to ideally dissipate the maximum wave energy a $G_0$ value around 0.5 should try to be obtained.

![Energy Coefficients vs. Go](image)

Figure 15- Energy Coefficients as $G_0$ increases.

Using wavemaker theory the actual observed amplitudes and the theoretical amplitudes can be compared to determine if the wavemaker is creating waves as
theorized. A comparison of the theoretical results along with the average recorded wave heights can be seen below.

Table 1- Comparison of wave amplitude from wavemaker theory to actual recorded amplitude.

<table>
<thead>
<tr>
<th>Stroke</th>
<th>Theoretical a (in.)</th>
<th>Actual a (in.)</th>
<th>% decrease</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.825 in</td>
<td>0.601466944</td>
<td>0.556267381</td>
<td>7.514887356</td>
</tr>
<tr>
<td>0.75 in stroke</td>
<td>0.546788</td>
<td>0.480017</td>
<td>12.21158</td>
</tr>
</tbody>
</table>

While there is a percentage decrease in amplitude between the theory and the recorded waves there are two main explanations for these losses. The first part of the loss in amplitude is due to friction as the wave travels down the flume and as the paddle of the wavemaker drags along the sides of the flume. The second reason for the loss in amplitude is the space under the bottom of the paddle which allows some water to pass under the paddle. This spacing occurs due to the flume bottom being inconsistent so the paddle had to be raised to just above the highest point to avoid dragging while in motion. Both of these factors led to the minor difference in wave height as compared to that from wavemaker theory.

The recorded transmission coefficient for 8 types of screens subject to waves generated with two different motor strokes (or waves with different wave height) while other factors remaining unchanged are presented in Table 2. The results indicate that, comparing to the incident wave heights, the transmitted wave heights are reduced at the same percentage for a given porous screen regardless of the incident wave amplitude. As would be expected a porosity of 40.31% screen can produce a lesser percentage of reduction in transmitted wave height than that from a 16.08% porosity screen. For the
screens with 0.125 inch pores, the percentages of wave height reduction in transmitted waves varies approximately from 14 % to 58% depending on the porosity.

Table 2- Recorded wave transmission coefficients for various screens with different incident wave height (different wave stroke length).

<table>
<thead>
<tr>
<th>Porosity</th>
<th>Pore size (in.)</th>
<th>0.75 in. Stroke</th>
<th>0.825 in. Stroke</th>
</tr>
</thead>
<tbody>
<tr>
<td>40.31%</td>
<td>0.125</td>
<td>0.63083</td>
<td>0.57939</td>
</tr>
<tr>
<td>29.61%</td>
<td>0.125</td>
<td>0.34884</td>
<td>0.35266</td>
</tr>
<tr>
<td>22.67%</td>
<td>0.125</td>
<td>0.26921</td>
<td>0.28844</td>
</tr>
<tr>
<td>16.08%</td>
<td>0.125</td>
<td>0.14219</td>
<td>0.14160</td>
</tr>
<tr>
<td>40.31%</td>
<td>0.25</td>
<td>0.75736</td>
<td>0.75162</td>
</tr>
<tr>
<td>29.61%</td>
<td>0.25</td>
<td>0.48204</td>
<td>0.54052</td>
</tr>
<tr>
<td>22.67%</td>
<td>0.25</td>
<td>0.40267</td>
<td>0.40867</td>
</tr>
<tr>
<td>16.08%</td>
<td>0.25</td>
<td>0.20236</td>
<td>0.18300</td>
</tr>
</tbody>
</table>

From the transmitted wave heights a comparison of the corresponding porosities with different pore sizes was completed. This comparison shows that 0.125 inch pores provide for a greater wave reduction (with smaller transmission coefficients) than 0.25 inch pores. It also shows that the effect of pore size is greater at larger porosities. For example at 40.31% porosity the difference in reduction due to pore size is greater than 12% while the corresponding difference at 16.08% porosity is only 5-6%. A graph showing these trends can be seen in Fig. 16.
As it can be seen the transmission coefficients are related to porosity with the plate porosities tested in this study. The graph also illustrates the effect of pore size at greater porosities as evidenced by the divergence of the transmission coefficients at greater porosities. In Fig. 17, the results were combined and trend lines were inserted to better illustrate this finding. The slope of the 0.125 inch line is 1.8586 and the slope of the 0.25 inch line is 2.2944. Both of these lines converge to the same point as they approach zero porosity as is expected because the effect of pore size is reduced as porosity is decreased. These trend lines do not necessarily mean that the relationship between transmitted wave height and porosity is linear but rather they serve to illustrate the divergence. With limited data points obtained this relationship cannot accurately be modeled, however, it may be linear and future modeling for more porosities is needed to test this theory.
The experimentally determined transmission coefficients can be used to evaluate the porous parameter $G_0$ (Eq. 13) and the eventual material property $b$ for the porous screens tested. Table 2 presents the $b$ values obtained from 2 hz (or period of 0.5 sec) wave data. This frequency (12.566 rad/sec) and water depth (0.75 ft) gave a wave number of 4.91(rad/ft). The values presented are the average “$b$” values for tests conducted with wave amplitudes of $a = 0.556$ in. and $0.48$ in.). These values were then considered as the calibrated “$b$” values for the given screens.

Table 3- Calibrated $b$ values from 2 hz transmitted wave.

<table>
<thead>
<tr>
<th>% OA</th>
<th>0.125 in. b (ft.)</th>
<th>0.25 in. b (ft.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>40.31</td>
<td>3.161E-06</td>
<td>7.000E-06</td>
</tr>
<tr>
<td>29.61</td>
<td>1.107E-06</td>
<td>2.195E-06</td>
</tr>
</tbody>
</table>
The average “b” values (Table 3) were then used to calculate $G_0$ for all of the screens. Under the same wave condition, the measured transmission coefficients, $T$, for each screen and the corresponding $G_0$’s were plotted against the theoretical results between $T$ and $G_0$ to further confirm the “b” values determined. As it can be seen our calibrated “b” values when applied to $G_0$ closely follow the theoretical solutions.

![T vs. $G_0$](image)

Figure 18- Experimental and theoretical $T$ vs. $G_0$ relationship

These calibrated “b” values were validated by using data obtained from other tests using incident waves with period of 0.56 sec (1.786 hz, or frequency of 11.22 rad/sec). With the new frequency the wave number for the same depth of water became
This new wave number was used to calculate $G_0$ again using the previously calibrated “b” values for the screen. The data of newly obtained transmission coefficients and $G_0$ values were added to $T$ vs. $G_0$ plot in Fig. 19. The comparisons in Fig. 19 conclude that the “b” values determined are applicable to all waves for the given screen and that “b” value does reflect as a material constant.

![Figure 19- Verification of “b” values and $G_0$ with different incident wave condition.](image)

Figure 19- Verification of “b” values and $G_0$ with different incident wave condition.

From the calibrated “b” values the following two figures (Figs. 20(a) and 20(b)) were prepared to show the theoretical wave surface profile for 1 ft amplitude incident waves. The first figure is for 0.125 in. pore size and the second for 0.25 in. pore size. In both figures the wave surface profile for the combined incident and reflected waves can
be seen to the right of \( x = 0 \) and the transmitted waves are shown to the left. In both cases the wave is traveling from right to left as shown by the arrows in both figures. From Fig. (20), we notice again the porous screen with smaller pore size results in transmitted waves with smaller wave heights.

Figure 20- Reflected and Transmitted Wave surface profiles for (a) 0.125 in pores and (b) 0.25 in pores.

To extend the use of the “b” value for screens with other porosities, the determined “b” values are plotted versus porosity for different pore size in Fig. 21 (thin
solid lines). It can be seen in Fig. 21 that “b” can be approximately governed by a power relationship between second and third order. The regression trend lines (thick solid lines) and regression equations are shown in Fig. 21. As it can be seen the “b” values show the divergence as porosity increases similar to the results presented in Fig. 17.

Figure 21- “b” values vs. porosity

**Conclusions**

In this study, analytical solutions for linear waves propagating past a porous screen are derived. The variation of transmission and reflection coefficients versus porous parameter is examined. It is found that the transmission coefficient increases as porous
parameter increases. Part of energy is dissipated as waves propagate past porous screens. Varios experiments have also been conducted to study the dissipation of energy for waves passing through a thin porous medium. There were multiple wave amplitudes and frequencies tested. There are three major findings obtained from the experimental study. The first one is that as porosity decreases transmitted wave height also decreases. The second is that for greater porosities the effect of pore size on the transmitted wave is also greater. The third and perhaps the most interesting conclusion is the experimental confirmation and calibration of the “b” value, which is related to the porous parameter, as a material constant. The calibrated “b” values were confirmed to be applicable to a given pore size and porosity even if amplitude and the wave number are changed. This study also confirmed experimentally the theory on porous medium interaction with linear progressive waves by Chwang (1983). While it appears “b” is governed by equation on the second to third order of the porosity, more tests of different porosities and waves are needed to obtain a better correlation between “b” value and the porosity for further application.

Acknowledgements

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References


Attachment 1

Φ = Wave equation

z = Vertical direction down to up being the increasing direction with the still water depth being z = 0

x = Horizontal direction with left to right being the increasing direction with the porous media location being x = 0

t = time

a = amplitude of wave (from z = 0 to crest or trough)

g = gravitational constant

λ = wavelength

k = wave number which is 2π/λ.

h = water depth from bottom of tank to z = 0

ω = frequency

η = wave surface profile equation

T = transmitted coefficient

R = reflected coefficient

G₀ = dimensionless porous effect parameter

ρ = 1.94 pcf

μ = 2.034 *10^-5 ft²/s

b = material constant having a unit of length

Re = Reynold’s Number

OA % = porosity or open area percentage

D= diameter of rounded hole

C = center to center distance of two holes

S = stroke length for wavemeker
**Attachment 2**

Round perforation screens 60 degree staggered 11 gauge thickness galvanized steel

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<th>D, in =</th>
<th>1/4</th>
<th>3/8</th>
<th>7/16</th>
<th>1/2</th>
<th>19/32</th>
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<td>7/16</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>O/A, % =</td>
<td>40.31</td>
<td>29.61</td>
<td>22.67</td>
<td>16.08</td>
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</tr>
</tbody>
</table>

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<thead>
<tr>
<th>D, in =</th>
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<tbody>
<tr>
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<tr>
<td>O/A, % =</td>
<td>40.31</td>
</tr>
</tbody>
</table>

Screens

1/8 in. 40.31%

1/8 in. 29.61%

1/8 in. 22.67%

1/8 in. 16.08%
¼ in. 40.31%  
¼ in. 29.61%  
¼ in 22.67%  
¼ in 16.08%