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Submerged Horizontal and Vertical Membrane Wave Barrier

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ABSTRACT: *In the present paper, the hydrodynamic properties of a Rahmen type flexible porous breakwater with dual fixed pontoon system interacting with obliquely or normally incident small amplitude waves are numerically investigated. This system is composed of dual vertical porous membranes hinged at the side edges of dual fixed pontoons, and a submerged horizontal membrane that both ends are hinged at the steel frames mounted pontoons. The dual vertical membranes are extended downward and hinged at bottom steal frame fixed into seabed. The wave blocking and dissipation mechanism and its effects of permeability, Rahmen type membrane and pontoon geometry, pretensions on membranes, relative dimensionless wave number, and incident wave headings are thoroughly examined.*

1. INTRODUCTION

During the past decades, there has been a gradual increase of interest in the use of the flexible plate or membranes as the desirable characteristics of being transportable, relatively inexpensive, rapidly deployable, easily detachable, and even sacrificial. Thus, it may be an ideal candidate as a portable and temporal breakwater for the protection of various coastal/offshore structures and sea operations requiring relatively calm sea states.

In this regard, the performance of a vertical screen membrane breakwater was investigated by Thomson et al. (1992), Aoki et al. (1994), Kim and Kee (1996), Williams (1996), Kee and Kim (1997), and Cho et al. (1997, 1998). The interaction of monochromatic incident wave with dual pre-tensioned, inextensible, vertical nonporous membrane wave barrier extending the entire water depth has been investigated by Edmond Y.M. (1998) using eigenfunction expansions for the velocity potential and linear membrane theory. Cho et al. (1998) developed an analytic solution for dual solid membrane system and a boundary integral method solution for more practical dual buoy/membrane wave barriers with either surface piercing or fully submerged system in oblique seas. The more practical and echo-friendlier breakwater system with fully submerged vertical porous membranes has been investigated by Kee (2001 a, b) in the two dimensional linear hydro elastic theories and Darcy's law, and found that it can be a very effective wave barrier along the wide frequency range, if it is properly designed.

On the other hand, the vertical elastic plate wave barriers clamped at the seafloor was investigated by Lee and Chen (1990) and Williams et al. (1991, 1992). Wang and Ren (1993a, 1993b) studied a thin beam like porous breakwater, and the wave trapping effect due to a flexible porous breakwater located in front of the vertical impermeable wall, and found that the efficiency of these flexible breakwaters can be improved by adding a structural porosity. The tuned two vertical screens also had been investigated by (Abul Azm, 1994).

The two dimensional problem of wave interaction with a horizontal porous flexible structure is of growing importance and significant studies in this area have been conducted by several authors. Yu and Chwang (1994) investigated the interaction of surface waves with a submerged horizontal porous plate. Cho and Kim (2000) studied the interaction of monochromatic incident waves with a horizontal porous flexible membrane in the context of two dimensional linear hydro elastic theory, and found that using a proper porous material can further enhance the overall performance of the horizontal flexible membrane. The proposed system was, however, relatively transparent to the incident wave field, especially in the long wave regime. In order to improve its performance at the long wave region, it is necessary for the structure to have a larger width, approximately one wave length, or to occupy the major fraction of water column. In view of this, an ideal Rahman type porous membrane breakwater system for the beginning stage of research was proposed by Kee (2002), which was composed of a fully submerged

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porous horizontal membrane hinged at the tips of dual vertical porous membranes hinged at seafloor, and found that such system can effectively reduce both of the transmitted and reflected wave heights.

In the present paper, the hydrodynamic properties of Rahman type porous membranes with dual fixed pontoons interacting with obliquely incident small amplitude waves are numerically investigated. This system is composed of one submerged horizontal (or slightly inclined) porous flexible membrane, and two vertical porous membranes hinged at the steel frame mounted on the dual pontoons and at beneath of pontoons, respectively. The two vertical membranes hinged at beneath of pontoons are extended downward, and hinged at a frame that fixed onto seabed, allowing gaps for the transportation of sediment or fishery. The fully submerged Rahmen type porous membrane breakwater is introduced herein in the points of view of marine scenario, water circulation, surface vessel passing, the reduced seabed erosion by standing waves in front of structure, and the reduced hydrodynamic pressures on the body of structures.

To assess the efficiency of this Rahmen type porous membranes system with dual pontoons, two dimensional hydro elastic formulation for two fluid domains was carried out in the context of the linear wave body interaction theory and Darcy's law for the wave energy dissipation through fine pores on the membranes. The fluid region is split into two regions, region (1) wave ward, over and in the lee of the structure, and region (2) inside of the structure. It is assumed, for simplicity, that the pre-tensioned membrane is thin, un-stretchable, and free to move only in the transverse direction for vertical membranes, and uniform in the longitudinal direction for the horizontal membrane. The pre-tension is assumed externally provided and much greater than the dynamic tension so as to be regarded as constant. The membrane dynamics is modeled as that of the tensioned string of zero bending rigidity, thus one dimensional linear string equation is applicable. The unknown complex velocity potentials of wave motion, which is containing diffraction and radiation, are fully coupled with deformations of membranes taking account for the fluid viscosity due to its porosity.

The developed theory and numerical model are validated by comparison with previously published numerical studies by Cho and Kim (2000) based on eigenfunction expansion of the limiting cases of the horizontal porous membrane in monochromatic waves. The relevant numerical results, presented in the paper, relate to the reflection and transmission coefficients. The corresponding wave forces and motions of membranes are also comparatively investigated, but not presented here. The performance evaluation has been conducted for the various parameters such as membrane permeability, Rahmen type membrane and pontoon geometry, pre-tensions on membranes, relative dimensionless wave numbers, and incident wave headings.

Results presented herein confirm that the overall performance of the Rahmen type flexible membranes with pontoons can be a very echo-friendlier breakwater system with an outstanding performance by tuning properly the system parameters, since the inclusion of permeability on membrane eliminates the resonance that aggravates the breakwater performance, and mutual cancellation effects between the incident waves and radiated waves by the motions of membranes, in addition, partial wave trapping effects through the gaps of pontoons. The performance of this type of breakwater is found to be highly promising for relatively wide range of frequency and wave headings, if it is properly tuned to the coming waves using the Rahmen's geometry including pontoon and membranes, pre-tensions, and permeability.

2. THEORY AND NUMERICAL METHOD

2.1 Governing Equations

The general features of the proposed system are depicted in Fig. 1. The horizontal membranes are hinged at the both frames mounted on the each floating pontoon. The initial tension is assumed to be given by the stiffeners between two pontoons. The pre-tension of vertical membranes should be supplied by the net buoyancy forces, however, is assumed to be given externally, since the motion of pontoon is restrained for simplicity for a second stage of research. The breakwater system with arbitrary porous and flexible boundaries is composed of a horizontal membrane with a width of W and with submergence depths df and dr below the still water level, and two vertical membranes that is extended downward and hinged at some distance from the sea bottom, allowing bottom gaps cf and cr. The height and width of pontoon are noted as a and b, respectively. The size of gaps between the hinged points of horizontal membranes and the top side of pontoons are noted as gf and gr, respectively. The sketch diagram is shown in Fig. 1. A Cartesian coordinate system (x, y) is defined with x measured in the direction of wave propagation from a point at mid-way between the vertical membranes, and y measure upward from the still water level. An obliquely incident, regular, small amplitude wave train of half height A and angular frequency ω propagates towards the breakwater with an angle θ with respect to x axis in water of constant depth h

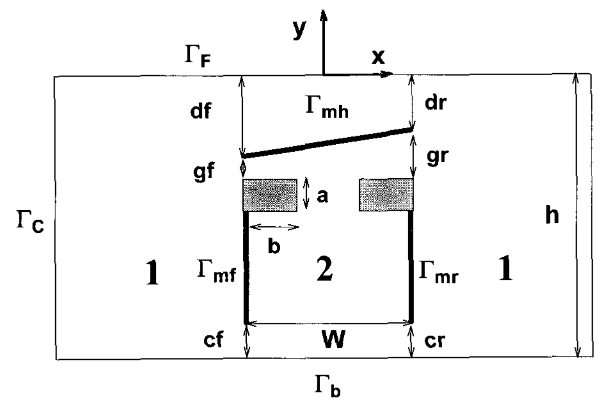


Fig. 1 Definition sketch and integration domains for Rahman type porous membrane with dual fixed pontoons.

If the fluid is assumed to be an ideal fluid such as incompressible, inviscid, and irrotational fluid, then the fluid motion can be described by velocity potential Φ that satisfies the Helmholtz equation $\nabla^2\phi_l - k_z^2\phi_l = 0$ within the fluid regions (Ω_l, $l=1,2$). In addition, the wave amplitude is assumed sufficiently small enough for a linear wave theory to apply. Consequently, Φ is subject to the usual boundary conditions, linearized free surface (Γ_F), rigid structures (Γ_S), bottom (Γ_b), and approximated far field conditions (Γ_C): (see, for example, Sarpkaya and Issacson, 1981). Thus Φ may be expressed in the following form:

$$\Phi(x,y,z,t) = Re[\{\phi_o(x,y) + \phi_l(x,y)\}e^{ik_z z - i\omega t}] \tag{1}$$

where ϕ_o is the well known incident potential, and can be written as;

$$\phi_o = \frac{-igA}{\omega}\frac{\cosh k_o(y+h)}{\cosh k_o h}e^{ik_o\cos\theta x} \tag{2}$$

Also, $Re[\ ]$ denotes the real part of a complex expression, $i=\sqrt{-1}$, t denotes time, and $k_z = k_o \sin\theta$ is the wave number component in the z direction. The wave number of the incident wave k_o is the positive real solution of the dispersion equation $\omega^2 = k_o g \tanh k_o h$ with g being the gravitational constant. And ϕ_l is time independent unknown scattered potentials in two fluid domains (see Fig. 1) includes both effects of diffraction and radiation.

2.2 Permeable Membrane Boundary Conditions

The required linearized kinematic boundary condition on the surface of the permeable flexible structure may be developed based on the formulation of Wang and Ren (1993a). This may be expressed for vertical membranes as:

$$\frac{\partial\phi_1}{\partial x} = -\frac{\partial\phi_2}{\partial x} = -i\omega\xi + u(y) \tag{3}$$

where $u(y)$ is spatial component of the normal velocity $U(y,t)$ of the fluid flow passing through a thin porous media, which is assumed to obey Darcy's law. The harmonic membrane motion is $Re[\xi e^{-i\omega t}]$. The porous flow velocity inside of membrane with fine pores $U(y,t) = Re[u(y)e^{-i\omega t}]$ is linearly proportional to the pressure difference between both sides of the thin membrane. Therefore, it follows that

$$U(y,t) = \frac{B}{\mu}(p_1 - p_2) = \frac{B}{\mu}\rho i\omega(\phi_1 - \phi_2)e^{-i\omega t} \tag{4}$$

where B is the constant called permeability having dimension of a length, μ is constant coefficient of dynamic viscosity, and ρ is constant fluid density. From Eqs. (3) and (4), $u(y)$ as an expression as follows:

$$u(y) = \frac{B}{\mu}\rho i\omega(\phi_1 - \phi_2) \tag{5}$$

The non-dimensional porosity parameter G commonly called Chang's parameter (Chang, 1983) is employed as follows,

$$G = 2\pi\rho\omega B / k_x u \tag{6}$$

This parameter can be regarded as a sort of Reynolds number representing the effects of both viscosity and porosity, considering the phase velocity of incident wave (ω/k_x) and a measure of porosity with a length dimension (B).

In order to match the two solutions on the surface of permeable membranes, ϕ and ξ the scattered potentials must also satisfy the following linearized dynamic boundary conditions on the membrane surface:

$$\frac{d^2\xi}{dy^2} + \lambda^2\xi = \frac{\rho i\omega}{T}(\phi_1 - \phi_2) \quad (\text{on } \Gamma_m) \tag{7}$$

where $\lambda=\omega/c$ and c is membrane wave speed given by $\sqrt{T/m}$ with T and m being the membrane tension and mass per unit length respectively.

2.3 Boundary Integral Equations

The fundamental solution (Green function) of the Helmholtz equation and its the normal derivative of G are given using the modified zeroth $K_0(k_z r)$ and first order $K_1(k_z r)$ Bessel function of the second kind (see, for example, Rahman and Chen, 1993), and where r is the distance from source point to the field point. After imposing the boundary conditions, the integral equations in fluid domain can be written as

$$C\phi_1+\int_{\Gamma_F}[k_z K_1(k_z r)\frac{\partial r}{\partial n}-\nu K_0(k_z r)]\phi_1 d\Gamma$$
$$+\int_{\Gamma_C}[k_z K_1(k_z r)\frac{\partial r}{\partial n}-ik_x K_0(k_z r)]\phi_1 d\Gamma$$
$$+\int_{\Gamma_m}[\phi_1 k_z K_1(k_z r)\frac{\partial r}{\partial n}+\frac{B}{\mu}i\rho\omega K_0(k_z r)(\phi_2-\phi_1)$$
$$+s1_{fhr} i\omega\xi K_0(k_z r)]d\Gamma+\int_{b,S}\phi_1 k_z K_1(k_z r)\frac{\partial r}{\partial n}d\Gamma$$
$$-\int_{\Gamma_S}K_0(k_z r)\frac{\partial\phi_0}{\partial n}d\Gamma \quad (\text{in } \Omega_1) \tag{8}$$

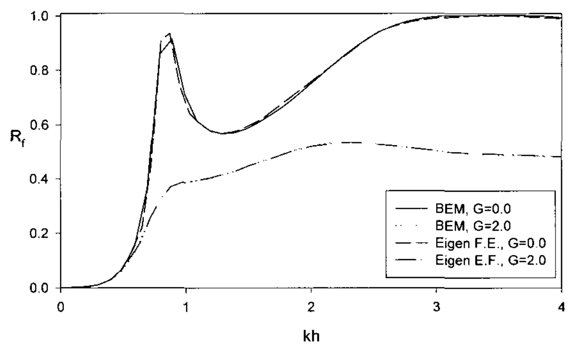
$$C\phi_2+\int_{\Gamma_m}[\phi_2 k_z K_1(k_z r)\frac{\partial r}{\partial n}+\frac{B}{\mu}i\rho\omega K_0(k_z r)(\phi_1-\phi_2)$$
$$-s2_{fhr} i\omega\xi K_0(k_z r)]d\Gamma+\int_{b,S}\phi_2 k_z K_1(k_z r)\frac{\partial r}{\partial n}d\Gamma$$
$$=-\int_{\Gamma_m}K_0(k_z r)i\rho\omega\frac{B}{\mu}\phi_0 d\Gamma-\int_{\Gamma_S}K_0(k_z r)\frac{\partial\phi_0}{\partial n}d\Gamma$$
$$(\text{in } \Omega_2) \tag{9}$$

where C is a solid angle constant, and $\nu=\omega^2/g$ is the infinite depth dimensionless wave number, the symbols of $s1_{fhr}=-,+,+$ and $s2_{fhr}=+,-,-$, are noted for the front vertical, horizontal, rear vertical membrane, respectively.

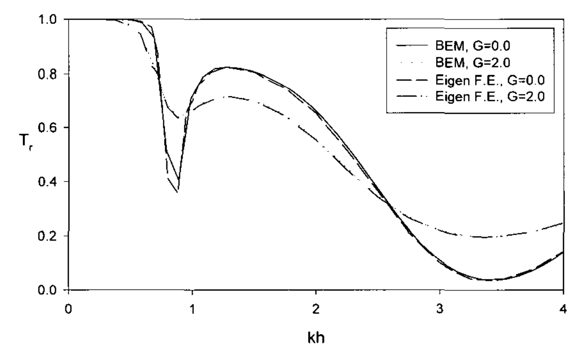
The integral equations (8) and (9) can be transformed to the corresponding algebraic matrix. The entire boundary is discretized into a large finite number of segments, and can be replaced by $N\times N$ matrix equations. Then, N includes numbers of segments along all boundaries, and there exist N unknowns for ϕ_1, ϕ_2, N_{mf}, N_{mh}, N_{mr} for membrane motions, which can be given in discrete form for each segment (see, for example, Kim and Kee, 1996). For two vertical non-porous membrane systems without horizontal membrane, the comparison of numerical results and analytical solution had been checked in the previous study (Cho et al., 1998).

3. NUMERICAL RESULTS AND DISCUSSIONS

A boundary integral equation method based on the distribution of simple sources along the entire boundary is developed for the numerical solution. The two vertical truncation boundaries are located sufficiently far from the edge of structures, usually 3~4 times of water depth away, such that far field boundary condition is valid, i.e. to ensure that the exponentially decaying local standing wave effect is negligible.



(a) reflection coefficients

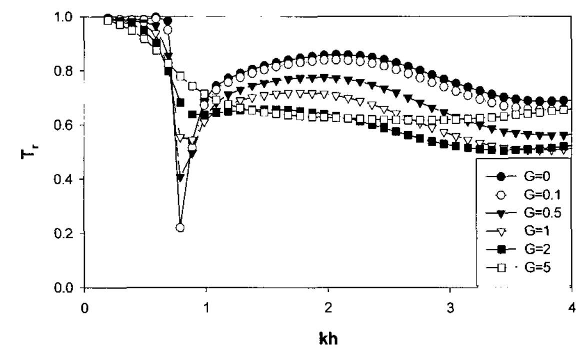


(b) transmission coefficients

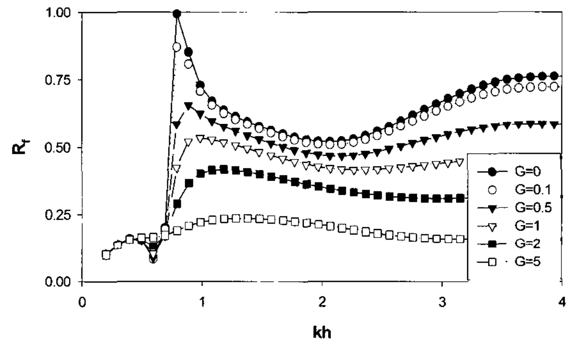
Fig. 2 Comparison of numerical method with analytic solutions for $dr/h=0.2$, $df/h=0.2$, $W/h=1.0$, $\theta=0°$, $\bar{T}=0.1$ $G=2.0$

The numerical results were checked against the energy conservation formula; $R_f^2+T_r^2=1$, since the energy relation is satisfied in the case of zero porosity (or an impermeable membrane). For a submerged horizontal membrane for $dr/h=0.2$, $df/h=0.2$, $W/h=1.0$, $\theta=0°$,

$G=2.0$, analytic solution has been developed by Cho and Kim (2000), and is compared to numerical results with good agreement as shown in Fig. 2 for dimensionless pre-tension of the horizontal membrane $\tilde{T}_h = 0.1$ The externally provided tension of membrane is normalized by $\rho g h^2$; $\tilde{T} = T/\rho g h^2$.



(a) transmission coefficients



(b) reflection coefficients

Fig. 3 Transmission coefficients (a) reflection coefficients (b) for various porosity parameter G as function of kh

Fig. 3 shows transmission and reflection coefficients as function of kh for the various porosity parameters G=0, 0.1, 0.5, 1, 2, 5 for a beam sea ($\theta=0$ °) and dimensionless pre-tensions of membrane $\tilde{T}_f = \tilde{T}_h = \tilde{T}_r = 0.1$ for the system geometry of $dr/h=0.2$, $df/h=0.2$, $gf/h=gr/h=0.1$ $b/W=0.35$, $W/h=1.0$, $cf/h=cr/h=0.1$, and $a/W=0.2$. The symbols $\tilde{T}_f, \tilde{T}_h, \tilde{T}_r$ represent the non-dimensional pre-tensions for a front vertical, a horizontal, and a rear vertical membrane, respectively. The reflection and transmission coefficients are gradually decreased as porous parameter G increases, up to G=2 where the transmitted wave starts to increase along the wide range of frequency. This kind of phenomena can be found easily in the deviation rate of energy relation as shown in Fig. 4. Thus, largest wave energy dissipation in harmonics with hydrodynamics of membranes may be directly related to the performance of a system as a wave barrier. For a higher porosity over the G=2, improperly larger transmitted waves surpass the wave blocking efficiency by the hydrodynamic effects of flexible system. The non-dimensional porous parameter G is linearly proportional to the permeability as $2\pi\rho\omega B/k_x\mu$ with a strong dependence of incident wave length. The porosity P on the flexible membrane equivalents to G based on the linear relation G=57.63P 0.9717 between porosity and porosity parameter, which was obtained from experiments for various porous plates (Han et al. 2003). This could be also a validation for the assumption that the permeability is not too high (say less than $B=1E-07m^2$) by Kim et al.(2000) to solve the wave interaction with arbitrary porous and rigid boundaries based on potential theory and Darcy' law. Thus, the permeability G=2 can be defined as an effective porosity that causes, generally along the wide frequency range, largest energy dissipation for a system with given various parameters as shown in Fig. 4.

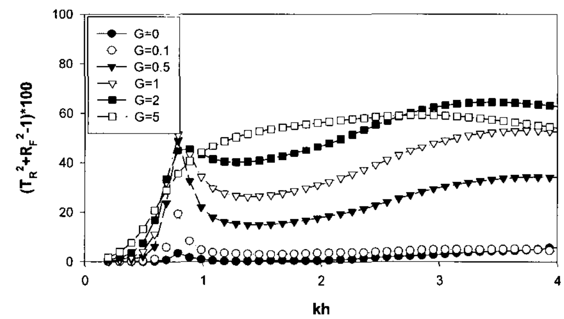
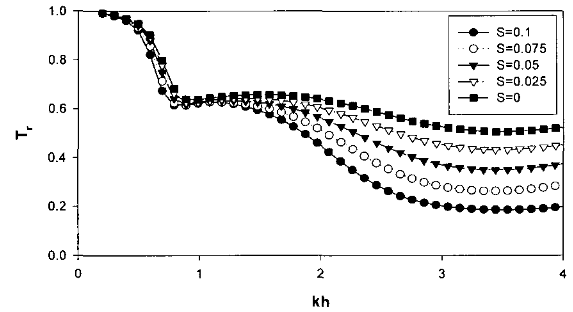


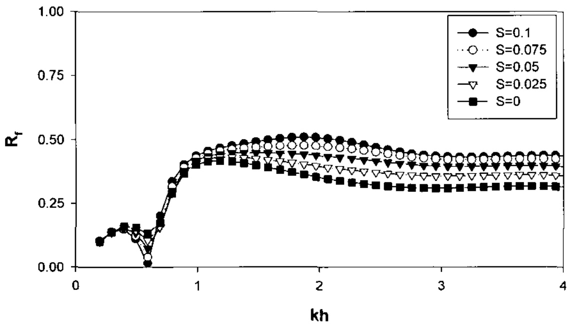
Fig. 4 The deviation rate of energy relation for various porosity parameter G as function of kh

The performance of such system is not impressive, compared to the performances of a tuned system (Kee, 2002) in the previous stage of research. It is mainly due to the transmitted waves in the lee side through the clearances between horizontal membranes and pontoons, in addition, the gaps between the ends of membranes and seafloor, which is intentionally designed in order to obtain the validation of the eco-friendlier system. Thus, a slightly inclined horizontal flexible porous membrane is employed for further wave energy dissipation in order to improve its efficiency.

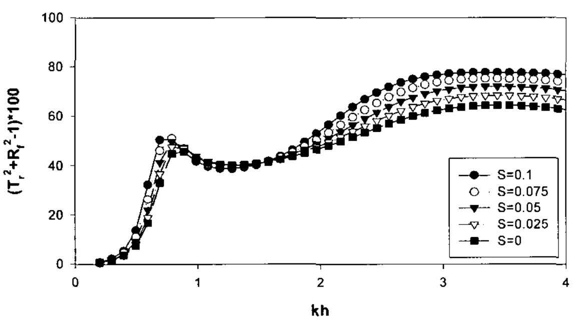
Fig. 5 shows the transmitted and reflected waves and also the deviated ratio from the energy relation for a inclined horizontal membrane system for various slopes changing from S=0 to S=0.1 with system geometries; $\widetilde{T}_f=\widetilde{T}_h=\widetilde{T}_r=0.1$ $a/W=0.2$, $b/W=0.35$, $gf/h=0.1$, $gr/h=0.2$, $df/h=0.2$, $dr/h=0.1$, and $cf/h=cr/h=0.1$ in a beam sea. The transmitted waves are dramatically reduced, as we intuitively expected, especially for the high frequency regime, mainly due to the further energy dissipation, by the circular motions of short frequency waves partially in the vertical direction, and mutual cancellation between the incidents waves and the generated waves by the motions of membranes.



(a) transmission coefficients



(b) reflection coefficients



(c) energy relation

Fig. 5 Transmission coefficients (a), reflection coefficients (b) and the deviation rate of the wave energy relation (c) for various inclines of horizontal membrane S as function of kh

Thus, this eco-friendly system with a slightly inclines shows generally better performance compared to the horizontal membrane only system as shown in Fig. 3. The reflected waves increase gradually, however, as the slope increase with larger wave energy dissipation as shown in Fig. 5c. It is very interesting to note that the further wave energy dissipation through fine pores can be obtained by the orbital motions of waves, passing through the slightily inclined horizontal porous flexible system.

At this point, we may expect intuitively that the performance of the inclined porous membrane only system may be affected negatively by the presence of the submerged pontoons, which has some gaps apart away from the inclined horizontal membrane. Thus, the performance has been checked for such various gap distances from $gf/h=0.05$, $gr/h=0.15$ to $gf/h=0.3$, $gr/h=0.4$, in a beam sea, with system geometries; $w/h=1.0$, $\widetilde{T}_f=\widetilde{T}_h=\widetilde{T}_r=0.1$ $cf/h=cr/h=0.1$, $dr/h=0.1$ $a/W=0.2$, $b/W=0.35$, and is shown in the Fig. 6.

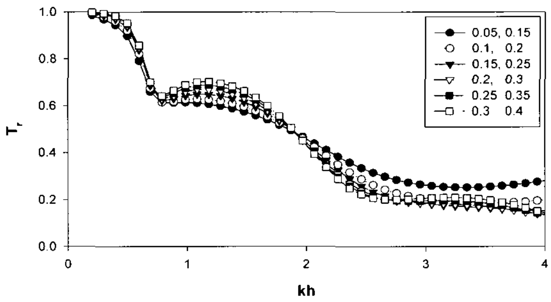


Fig. 6 Transmission coefficients for various $(gf, gr)/h$ as function of kh

The shortest upper gap distance with $gf/h=0.05$, $gr/h=0.15$ has a better efficiency for the frequency range of $0.9\leq kh\leq 1.6$, however, a poor efficiency for higher frequency ranges. For the frequency range of $0.9\leq kh\leq 1.6$, the effects of gap distances are gradually worse as the gap increases. The system with $gf/h=0.1$ $gr/h=0.2$ has good performances, in general, along the wide frequency range, however, the gap distance effects are not significant except for a limited frequency range. If the geometry variation, in the vertical direction, of the structure does not influence its performances, it can be further validated by the performance evaluation for the various front bottom gap cf/h, which has an equivalent membrane length for a system with $W/h=1.0$, $a/W=0.2$, $b/W=0.35$, $df/h=0.2$, $dr/h=0.1$, $\widetilde{T}_f=\widetilde{T}_h=\widetilde{T}_r=0.1$ $gf/h=0.1$, $gr/h=0.2$, $cr/h=0.1$, and are shown in Fig.

7 for $\theta=0^\circ$. We also checked the efficiency when the both bottom gaps $(cf, cr)/h$ vary for the pervious system geometry; the vertical membranes are shortened, and shown in Fig. 8. The varying performance for the shortened length of membranes is very similar to the trends that are found in Fig. 6. Therefore, we can tentatively conclude that the wave energy dissipation and mutual cancellation mechanism of the fully submerged slightly inclined horizontal porous flexible membrane function relatively well regardless of the sub-structure geometry.

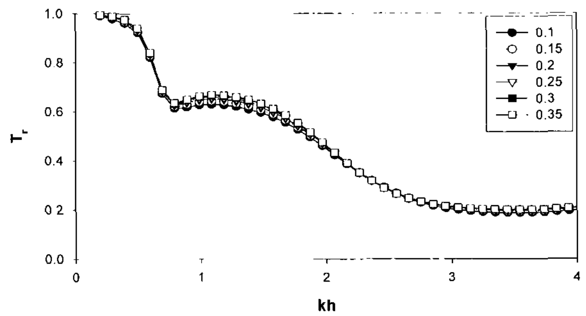


Fig. 7 Transmission coefficients for various cf/h as function of kh

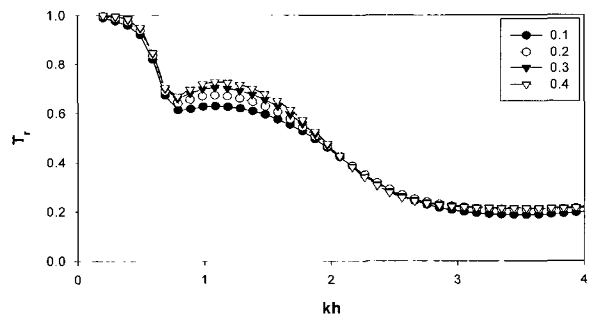


Fig. 8 Transmission coefficients for various $(cf, cr)/h$ as function of kh

The performance of the various width of pontoon, which is consisting of the sub-structure geometry, has been investigated since a larger distance between two pontoons in horizontal direction allows more water circulation in the vertical direction. The blockage effects, depicted in Fig. 9, are very manifest for the range of $kh \geq 1$, especially for the wider pontoons, which has small gaps, blocking major space in the vertical direction. Thus, finally we can conclude that the geometry variation of the sub-structure in vertical direction does not influence significantly the performances of the proposed system.

Based on the result analysis so far, we may conjecture that horizontal system only with pontoons may be a good choice as an efficient wave barrier. The pontoons are needed to support the steel frame to supply the initial membrane tension mechanically and keep the floating and submerged status. In a while, Fig. 9 shows the performance variation for the various width of pontoon b/W for a system with $\widetilde{T_f}=\widetilde{T_h}=\widetilde{T_r}=0.1$, $w/h=1.0$, $a/W=0.2$, $dr/h=0.1$, $cf/h=cr/h=0.1$, $df/h=0.2$, $gf/h=0.1$, $gr/h=0.2$, and for $\theta=0^\circ$, the small size of pontoon with rectangular shape has much better efficiency compared to the wider one, thus one can easily expect that small initial tension of vertical flexible membranes must be supplied by its net buoyancy force.

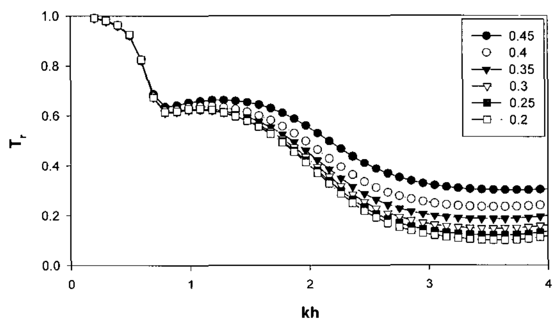


Fig. 9 Transmission coefficients for various b/W as function of kh

In this second stage of research, the motion of pontoon was restricted for simplicity, and the initial tension of vertical porous membrane are assumed to be given by externally. In here, the initial tension can be reduced as an order of one, such as $\widetilde{T_f}=\widetilde{T_r}=0.01$ considering the fully submerged geometry of pontoons. Thus, after imposing the proper non-dimensional tension ($\widetilde{T_{fr}}$) on the both of front and rear vertical membranes for a system with $a/W=0.2$, $b/W=0.2$, $W/h=1.0$, $\widetilde{T_h}=0.1$, $df/h=0.2$, $dr/h=0.1$, $gr/h=0.2$, $gf/h=0.1$, $cf/h=cr/h=0.1$, the efficiency in the beam sea has been checked, and shown in Fig. 10. The weaker tension has been dramatically improved performances in the lower frequency range, however sacrificing its performance in the short wave length regions, since the weakly tensioned membranes may allow relatively large motions, which generates propagating wave in lee side. In the frequency range of $0.7 \leq kh \leq 1.5$, the mutual cancellation effects between the incident waves and radiated waves by the motion of membranes are very clearly presented.

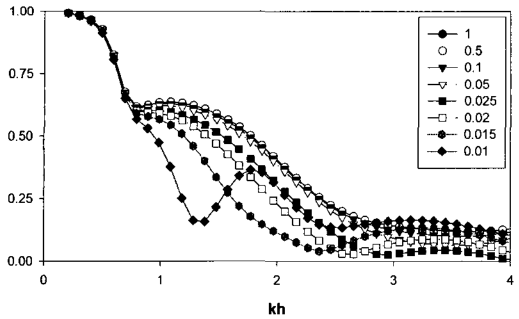
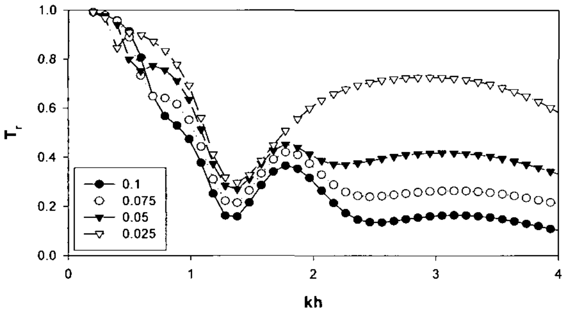
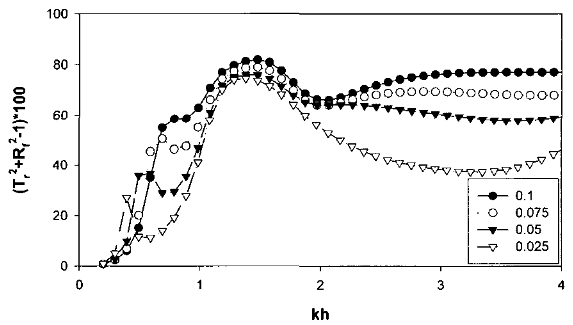


Fig. 10 Transmission coefficients for various ($\widetilde{T}_{fr}$) as function of kh



(a) transmission coefficients



(b) energy relation

Fig. 11 Transmission coefficients (a) and the deviation rate of energy relation (b) for various $\widetilde{T}_h$ as function of kh

The performances was investigated for the various initial tensions of the inclined horizontal porous membranes $\widetilde{T}_h$ for $\widetilde{T}_f = \widetilde{T}_r = 0.01$ $b/W = 0.2$, $W/h = 1.0$, $a/W = 0.2$, $cf/h = cr/h = 0.1$, $df/h = 0.2$, $dr/h = 0.1$, $gf/h = 0.1$, $gr/h = 0.2$, and shown in Fig. 11 for $\theta = 0$ °. The taught tension of the slightly inclined porous horizontal membrane has larger wave energy dissipation as shown in Fig. 11b. It is interesting to note that the performance becomes worse as the initial tension decreases. It is also interesting to note that relatively large motions of the horizontal membrane usually aggravate the wave energy dissipation effects through fine pores.

The motion of membranes corresponding to each equally given vertical membrane pre-tensions $\widetilde{T}_f = \widetilde{T}_r = 0.01$ was investigated for the system geometries of $b/W = 0.2$, $a/W = 0.2$, $W/h = 1.0$, $cf/h = cr/h = 0.1$, $df/h = 0.2$, $dr/h = 0.1$, $gf/h = 0.1$, and $gr/h = 0.2$ in a beam sea. The non-dimensional motion amplitudes and its contours as shown in Figs. 12,13, respectively. The motions of weakly tensioned membrane are intuitively expected to be larger, however, such expectation is not always correct. Since the wave energy dissipations are linearly proportional to the pressure gradient between both sides of membranes, in addition, the wave energy dissipation behaves as a damper for the system.

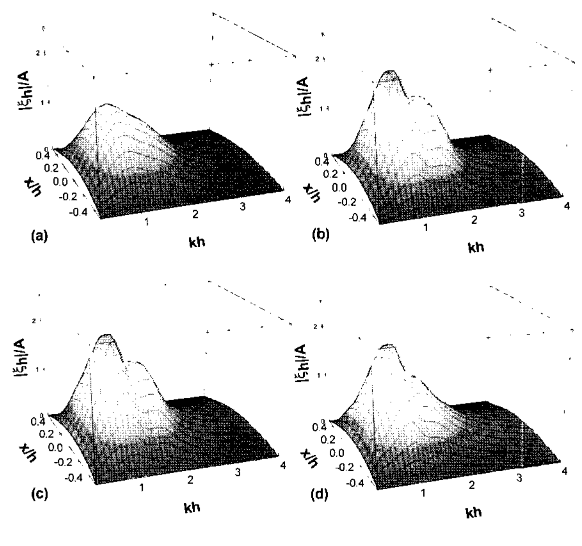


Fig. 12 Non-dimensional motion amplitude of horizontal membranes for $\widetilde{T}_h = 0.1, 0.75, 0.5, 0.25$ noted as (a), (b), (c), (d), respectively

Therefore, we may expect that even weak initial tensioned membrane system can occasionally have less membrane motions due to damping effects at the frequency of $kh = 1.5$ as shown in contour plots Figs. 13b,c,d. In contrary to the motion of the vertical flexible system, the motion of the weakly tensioned horizontal porous membrane does not generate the propagating waves in lee side.

The general performance of the proposed system in the obliquely incident waves for a system with $W/h=1.0$, $a/W=0.2$, $b/W=0.35$, $df/h=0.2$, $dr/h=0.1$, $gf/h=0.1$, $gr/h=0.2$, $\widetilde{T}_f=\widetilde{T}_r=0.01$ and $\widetilde{T}_h=0.1$ was investigated as shown in Fig. 14. The amplitudes and contours of transmitted and reflected waves for the varying wave heading from 0° to 85°. The wave blocking (includes mutual cancellation and partial wave trappings) and energy dissipation efficiencies are outstanding for the range of $\theta=0^{\circ}\sim35^{\circ}$. For the higher wave heading and high frequency region, approximately 50% of incident waves are transmitted; instead almost all waves are blocked for a very high wave heading. However, the reverse trend appears in the reflection coefficients, allowing almost all waves are reflected. It is interesting to note that the wave energy dissipation effects become negligible for the high wave heading regions, as shown in Fig. 14.

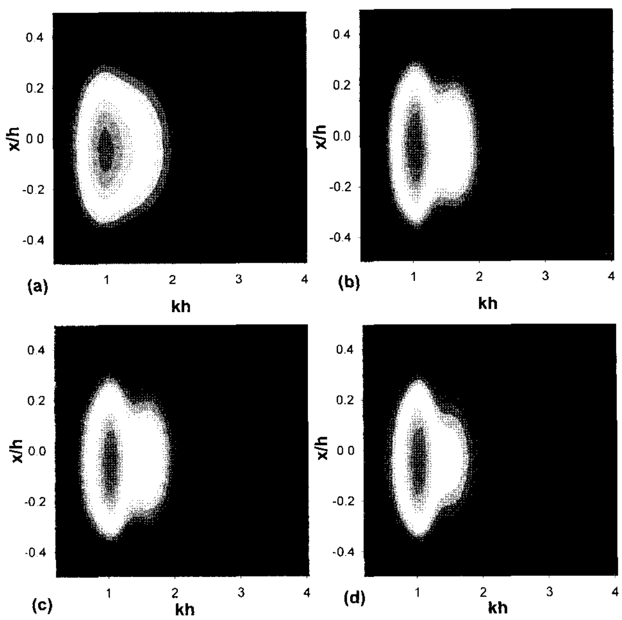


Fig. 13 Contour plots for non-dimensional motion amplitude of horizontal membranes for $\widetilde{T}_h=0.1, 0.75, 0.5, 0.25$ noted as (a), (b), (c), (d), respectively

The wave forces exciting on the porous membranes are depicted in Fig. 15 for a front vertical, a horizontal, and a rear vertical porous flexible membrane, respectively. The forces on the front vertical membranes are quite larger than those of rear one, as we expect intuitively. For the large membrane motion at $kh=1.3$ which is greater than the motion at low frequency, i.e. large wave length, the corresponding wave transmission coefficient is slightly bigger than the others as shown in Fig. 14. Thus, it can be called as a resonance frequency in a system. Such larger force may generate the large motion of membranes which generate large wave propagating into the rear membrane.

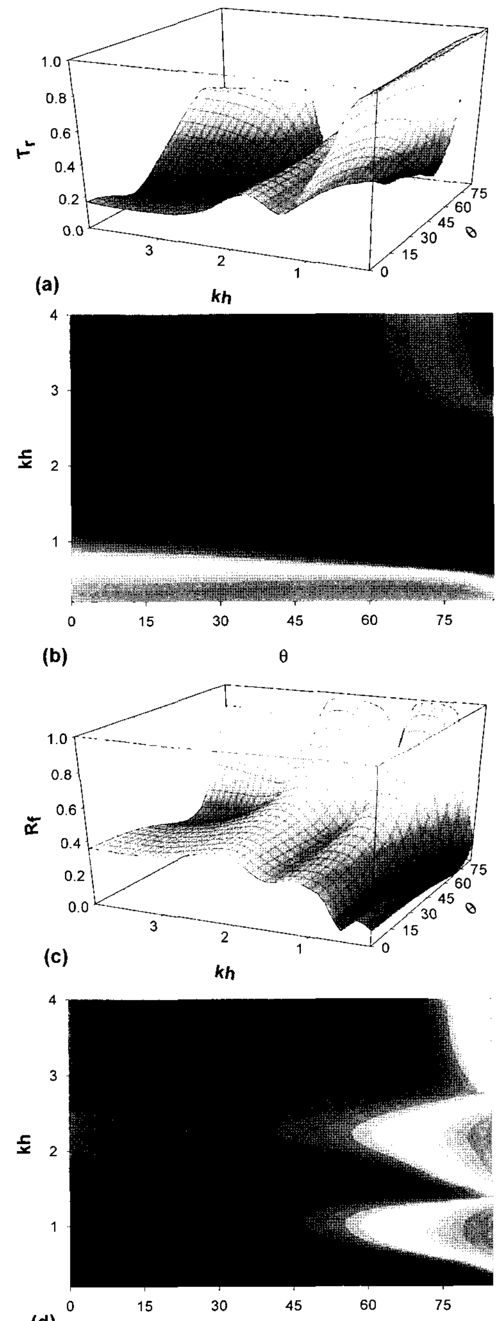


Fig. 14 Transmission coefficients (a), transmission contours (b), reflection coefficients (c), reflection contours (d) against various wave headings as function of kh

If such generated waves are, however, mutually canceled based on the phase differences of the radiated waves or dissipated inside of system through the fine pores on membranes. Then, the forces on the rear membrane is not such large so as to allows that relatively moderate rate of the incident or radiated waves are transmitted into lee side as shown in Fig. 14. In contrast to the performances at the such resonance frequency, the efficiency of the wave blockage and dissipation at the long wave regions are very poor mainly due to the large forces on the membranes.

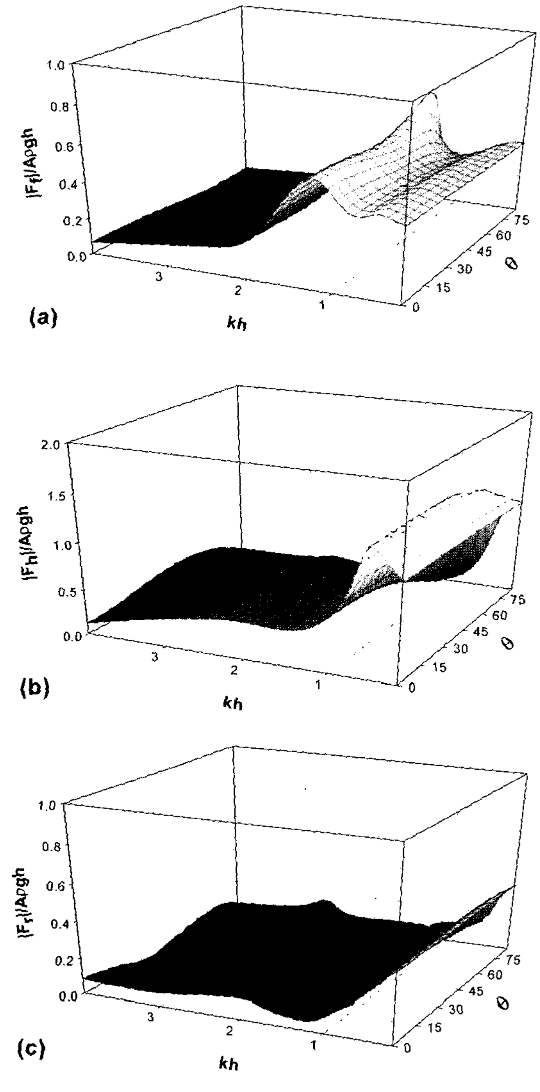


Fig. 15 Non-dimensional wave force on the body of membranes for front vertical (a), horizontal (b), rear vertical (c) against various wave headings.

4. SUMMARY AND CONCLUSIONS

The interaction of oblique incident waves with a Rahman type porous flexible membrane breakwater with dual fixed pontoons, for simplicity, was investigated in the context of 2D linear hydro elastic theory based on the Darcy's law due to fluid viscosity. Properly adjusted 2-D BEM code has been developed for parametric study to figure out major parameters influencing its performances. The developed program for the porous problem has been checked against the analytic solution for limited cases, and found that it is in good agreement. Using the developed program, we investigated the general performance of an ideally suggested echo-friendlier system which is conceptually designed to get the mutual cancellation, wave energy dissipation, partial wave trapping mechanism. Thus the geometry is quite complicated and has following parameters; the various submergence depth measured from the free surface to the top of horizontal membranes, width of horizontal membrane, pre-tensions, permeability, the geometry of pontoon, gap distances from the seafloor to the tip of membranes or from the top of pontoon and the tip of horizontal membranes. Based on the results analysis, it is found that the optimal system with an effective porous parameters $G \approx 2$ can significantly improved the overall performances as a wave barrier along the wide range of incident waves frequencies and headings compared to the case of horizontal porous membrane only. It was also found that the horizontal flexible porous membrane system with slightly inclines could be a better choice for the enhancement of wave energy blocking and dissipating efficiencies using the geometric positioning against the various orbital motions of waves according to the incident wave length. In addition, the weakly tensioned vertical membranes and highly tensioned horizontal membrane were found to be a very effective wave barrier for the relatively long wave regions, due to the characteristics of wave energy dissipation and mutual cancellation inside of a system.

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