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Acoustic Waves in a Fluid with Porous Solids

LIANG-HSIUNG HUANG

Department of Civil Engineering and Hydrotech Research Institute
National Taiwan University
Taipei, Taiwan, R.O.C.

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ABSTRACT

The literature on acoustic waves in a fluid interacting with porous solids is reviewed in the present paper. In addition, the author's related works are divided into three catagories, poroelastic media, rigid screens, and noise barriers, and then discussed. A summary of the author's works in these three catagories is given, and important results are presented.

Key Words: acoustic wave, poroelastic media, rigid screens, noise barriers

I. Introduction

The propagation of sound in a porous material has received considerable attention over the years. The earliest work was done by Zwikker and Kosten (1949), but they neglected the effects of dilatation of the frame and the rotational wave. A general approach to sound propagation in the porous media was developed by Biot (1956a, 1956b), who employed the dilational and rotational modes of propagation for both low and high frequencies. The basic assumptions in Biot's theory are that the viscous dissipation of a fluid obeys Darcy's law, and that the solid frame obeys the law of linear elasticity. Solutions to Biot's equations indicate that disturbances in a porous medium can be transmitted by three different waves. The first two are longitudinal waves, and the third is a transverse wave. The experiments carried out by Hovem and Ingram (1979) and other researches have confirmed that Biot's theory is a proper model for sound propagation in porous materials.

There are many applications of Biot's theory, such as the effects of boundaries on wave propagation in a liquid filled porous solid studied by Deresiewicz (1960, 1961, 1962, 1964a, 1964b, 1965, 1974), Deresiewicz and Rice (1962, 1964), Deresiewicz and Wolf (1964), and Deresiewicz and Levy (1967), one dimensional longitudinal waves studied by Geertsma and Smit (1961), the attenuation of which in saturated sediments was studied by Stoll and Bryan (1970) and Stoll (1974, 1977), Rayleigh waves in a poroelastic half-space investigated by Jones (1961) and later corrected by Tajuddin (1984), Stoneley waves studied by Markov and Yumatov (1987), and a boundary layer correction approximation obtained by Mei and Foda (1981). Recently, the present author and his colleagues conducted a series of studies (Huang and Song, 1993a; Chen *et al.*, 1997; Lin *et al.*, 1996; Ou Yang *et al.*, 1998) on water waves interacting with poroelastic media.

For the application of Biot's theory to acoustics, Huang and Chwang (1990b) analyzed the trapping and absorption of undesirable underwater sound by a layer of porous medium over a sphere in order to maximize the energy dissipation within a continuous spectrum of wave frequencies. The Biot theory was applied to the porous layer, and the linearized sound-wave equation was used for the homogeneous fluid outside the layer.

Besides acoustic waves acting on a finite object in an unbounded field, the influence of the seafloor on the acoustic plane wave is an old problem. The related references can be found in many earlier works, such as those Brekhovskikh (1980), Roetman and Kochhar (1976) etc. However, due to the complexity of the porous material of the seafloor, these earlier studies over-simplified the model for the porous material. Recently, the problems of plane acoustic waves acting on an infinite interface between water and a poroelastic seafloor of both infinite and finite thickness were studied by Huang (1992).

The more complicated problem of a periodic acoustic point source in a shallow sea affected by a free surface and a flat seafloor is not only interesting in fundamental acoustics, but also practical in real life. Since the slow attenuation of acoustic waves always causes trouble at the outer boundary for computation, a simple application of the solution to this problem is to provide a better outer boundary condition for numerical computation. Kinsler *et al.* (1982) solved the problem using the normal mode method for assumed rigid and fluid seafloors. Brekhovskikh (1980) treated the same problem by expanding the point source into plane wave integration with known plane wave reflection coefficients of the interfaces. However, when the seafloor is porous, the normal mode method fails because of the energy dissipation within the porous medium. On the other hand, because a satisfactory plane wave reflection coefficient of the porous interface was not found, the method Brekhovskikh applied was not successful either. Chen and Huang (1992) analyzed a periodic acoustic point source in a shallow sea affected by a free surface and seafloor. Sea water was treated as a slightly compressible homogeneous inviscid fluid, and the material of the seafloor was assumed to be poroelastic.

Unlike the subject of layered media affected by acoustic waves, there have been few studies on sound waves with a screen as part of the boundary. Earlier investigations on the damping effect of a screen can be found in Zwikker and Kosten (1949). Another study of the screen effect on sound waves was conducted by Leppington and Levine (1973). Huang and Chwang (1990a) studied the boundary-value problems of linear sound waves for a sphere surrounded by a concentric screen. Both the radiation caused by the surface vibration of the sphere and the scattering of an incoming plane wave by the sphere were investigated. The boundary condition on the normal velocity of the fluid passing through a screen, as proposed by Taylor (1956), was applied.

The interaction of an acoustic wave and a screen is very important in engineering practices in acoustics, especially in noise control. Therefore, correct simulation or description of the interaction between an acoustic wave and a screen is very important and worth studying. However, due to the complexity of the flow passing through the screen and the complexity of the screen itself, problems of this kind with two-phase flow involved are usually too messy to handle. Fortunately, for cases where noise in the air passes through a porous medium, because the compressibility of air is usually much greater than that of the solid skeleton of the porous medium, these problems can be drastically simplified. Furthermore, if the porous medium is thin, then the problems become even simpler. Indeed, Huang and Song (1993b) did propose a rigorous boundary condition for solving problems of noise in the air passing through a rigid screen. By using the proposed approach, the problem of an oscillating plane rigid screen was also solved by Huang and Song (1993b).

The mitigation of noise pollution is becoming more and more important in view of environmental protection. There have been many researches on traffic noise measurement in Taiwan, e.g., Hsu (1994, 1995) etc., and they did contribute much to engineering practice. However, theoretical analyses of traffic noise in Taiwan have been rare. Huang and Kung (1992a) simulated the noise barrier problem using a still, single freguency, and three dimensional sound source located within two parallel porous medium layers with rigid back walls. The solution of the reflection sound field was represented by an asymptotic solution which was derived using the method of steepest descent. The infinite reflections in Chen and Huang (1992) and the theory of poroelasticity was adopted to analyze the problem of the interaction between transportation noise and a noise barrier. However, since the density of the air is rather small compared to the density of the porous medium, the skeleton of the porous medium was assumed to be rigid. On the other hand, after replacing the porous medium layer with a rigid screen, the method of steepest descent was applied to study a noise barrier simulated by a rigid screen with a back wall (Huang and Kung, 1992b).

Application of the boundary integral element method to exterior problems of acoustics has become very popular because of its superiority in handling the far field condition of unbounded problems. Furthermore, it can reduce one computational dimension and take care of the complicated diffraction effect. For example, Meyer *et al.* (1978) solved the problem of sound scattering due to bodies of arbitrary shape using the boundary integral element method; Seybert *et al.* (1985) applied the concept of isoparametric element to boundary integration and attacked the similar problem of Meyer *et al.* (1978); Huang (1991) also studied acoustic diffraction of double connected bodies using the boundary integration method. However, the above investigations usually failed to handle problems with arbitrary boundary acoustic impedance. For instance, although Huang (1991) tried to solve problems with hard and soft boundaries separately, problems with imperfectly soft boundaries were left unsolved.

The boundaries in Huang and Kung (1992a, 1992b) were much simplified, such that the important diffraction effect was not included. Furthermore, in simulating a heavy traffic area, a two-dimensional sound source is more reasonable than the three-dimensional one applied by Huang and Kung (1992a, 1992b). Hsiao and Huang (1994) studied the diffracted sound field of noise barriers using a two-dimensional boundary integral element method. By dividing the computation into two catagories based on the specific acoustic impedance of the boundary, problems with arbitrary boundary acoustic impedance can be handled easily.

In the following discussion of the interaction between porous solids and acoustic waves in a fluid, the author's works will be reviewed and divided into three catagories. They are, in sequence, poroelastic media, rigid screens, and noise barriers.

II. Poroelastic Media

Huang and Chwang (1990b) considered the trapping and absorption of small-amplitude sound waves by a layer of porous medium over a sphere (Fig. 1). The Biot theory of poroelasticity was applied to the porous layer, and the linearized sound-wave equation was used for the homogeneous fluid outside the layer.

The Biot theory of poroelasticity states that

$$\nabla \cdot \underline{\underline{\sigma}}^* = \rho_{11}\frac{\partial^2 \underline{d}^*}{\partial t^2} + \rho_{12}\frac{\partial^2 \underline{D}^*}{\partial t^2} + b\left(\frac{\partial \underline{d}^*}{\partial t} - \frac{\partial \underline{D}^*}{\partial t}\right), \quad (1)$$

$$\nabla \cdot \underline{\underline{S}}^* = \rho_{12}\frac{\partial^2 \underline{d}^*}{\partial t^2} + \rho_{22}\frac{\partial^2 \underline{D}^*}{\partial t^2} - b\left(\frac{\partial \underline{d}^*}{\partial t} - \frac{\partial \underline{D}^*}{\partial t}\right), \quad (2)$$

with

$$\frac{\partial P^*}{\partial t} = -\frac{K}{n_o}\left[(1-n_o)\nabla \cdot \left(\frac{\partial \underline{d}^*}{\partial t}\right) + n_o \nabla \cdot \left(\frac{\partial \underline{D}^*}{\partial t}\right)\right], \quad (3)$$

$$\underline{\underline{\sigma}}^* = \underline{\underline{\tau}}^* - (1-n_o)P^* \underline{\underline{I}}, \quad (4)$$

$$\underline{\underline{\tau}}^* = 2G\underline{\underline{e}}^* + \lambda(\nabla \cdot \underline{d}^*)\underline{\underline{I}}, \quad (5)$$

$$e^*_{ij} = (d^*_{i,j} + d^*_{j,i})/2, \quad (6)$$

$$\underline{\underline{S}}^* = -n_o P^* \underline{\underline{I}}, \quad (7)$$

$$\rho_{11} = (1-n_o)\rho_s + \rho_a, \quad (8)$$

$$\rho_{12} = -\rho_a, \quad (9)$$

$$\rho_{22} = n_o \rho_f + \rho_a, \quad (10)$$

$$b = \mu n_o^2 / k_p, \quad (11)$$

where $\underline{\underline{\sigma}}^*$ is the solid stress tensor, $\underline{\underline{\tau}}^*$ is the effective stress tensor of the solid skeleton, $\underline{\underline{S}}^*$ is the normal stress tensor of the fluid, and $\underline{d}^*$ and $\underline{D}^*$ are solid and fluid displacement vectors, respectively. P^* is the perturbed pressure of the fluid inside the porous medium, ρ_s is the solid density, ρ_a is the mass coupling effect (which is neglected in the present study), n_o is the porosity, μ is the fluid viscosity, k_p is the specific permeability, G and λ are Lame constants of elasticity,

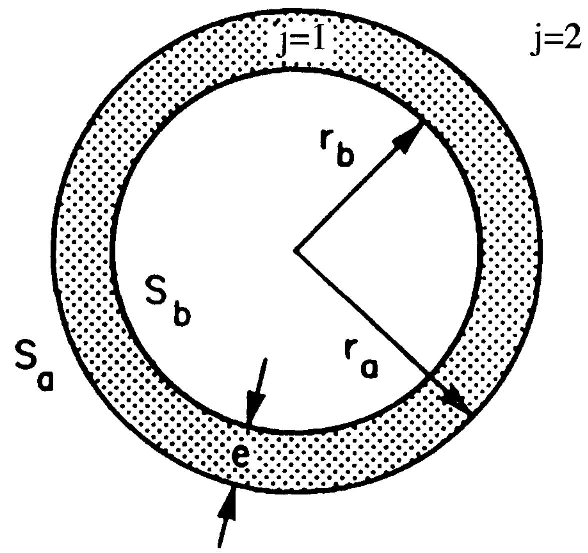

Fig. 1. Schematic diagram of a sphere covered by a porous layer.

K is the bulk modulus of compressibility of the fluid, and $\underline{\underline{I}}$ is the identity matrix.

With these equations and the boundary conditions on the sphere, on the porous medium-fluid interface and at the far field, a boundary-value-problem of Huang and Chwang (1990b) was thus formulated. By transforming oscillatory Biot's momentum equations into Helmholtz equations, i.e., (after getting rid of the oscillatory parameter $e^{-i\omega t}$)

$$\underline{d} = \nabla\phi_1 + \nabla\phi_2 + \nabla\times\underline{H}, \quad (12)$$

$$\underline{D} = \alpha_1\nabla\phi_1 + \alpha_2\nabla\phi_2 + \alpha_3\nabla\times\underline{H}, \quad (13)$$

and

$$\nabla^2\phi_j + k_j^2\,\phi_j = 0,\ j=1,\ 2, \quad (14)$$

$$\nabla^2\underline{H} + k_3^2\underline{H} = \underline{0}, \quad (15)$$

where k_1, k_2, and k_3 are wave numbers and α_1, α_2 and α_3 are fluid/solid related parameters, the method of separation of variables was applied to solve the problem.

The relative acoustic powers for single-mode vibrations, E^R_{10}, and for plane-wave scattering, E^S_{10}, are defined as

$$E^R_{10} = \frac{E^R_1}{E^R_0}, \quad (16)$$

$$E^S_{10} = \frac{E^S_1}{E^S_0}, \quad (17)$$

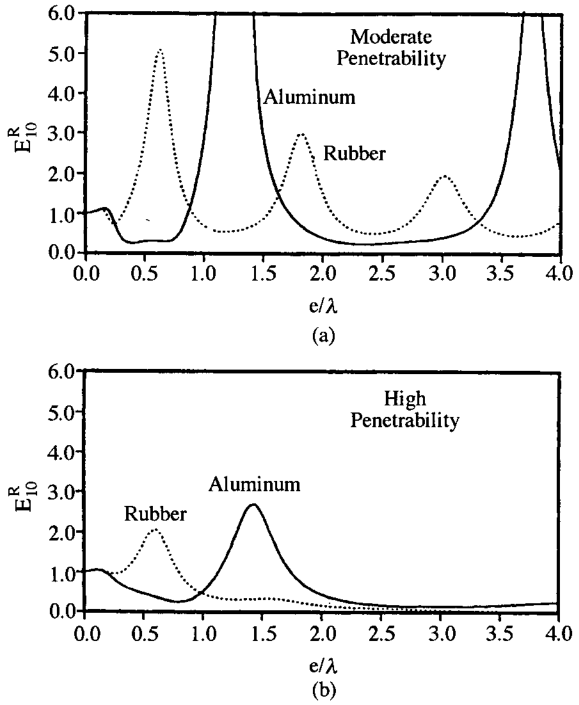

Fig. 2. Relative acoustic power E^R_{10} versus the layer thickness-to-wavelength ratio e/λ for (a) a moderately pentrable layer, (b) a highly penetrable layer.

where E^R_1 and E^S_1 are nondimensional acoustic powers of the present problem while E^R_0 and E^S_0 are dimensionless acoustic powers for a bare sphere. Figures 2 and 3 are numerical examples of relative acoustic powers versus the layer thickness-to-wavelength ratio e/λ for a moderately penetrable layer and a highly penetrable layer, respectively. From the numerical examples presented in Figs. 2 and 3, it is found that a highly penetrable material (i.e., high pore size, permeability, and porosity) has a better trapping and absorption effect than does a moderately penetrable material. A thick layer is generally preferable to a thin one. Because a stiff material has high elastic constants, its absorption effect is poorer than that of a soft material. However, for the scattering problem, the elastic response of a stiff material makes it a better choice for reducing the relative acoustic power, especially when e/λ is small. This result indicates that absorption may not be as important as trapping when the porous layer is thin. In summary, the sample results show that a sphere covered with a layer of poroelastic medium may not be a good device for reducing the sound radiation, but it is very good for reducing scattered sound.

The problems of plane acoustic waves acting on an interface between water and a poroelastic seafloor of both infinite (Fig. 4) and finite (Fig. 5) thicknesses

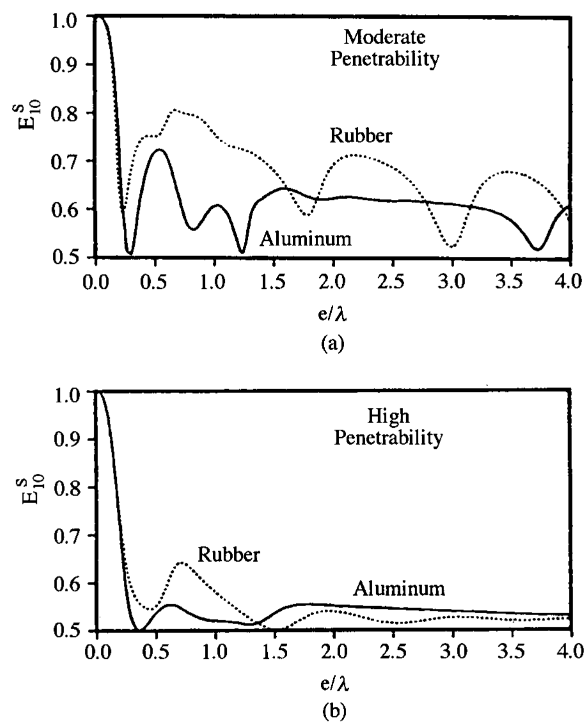

Fig. 3. Relative acoustic power E^S_{10} versus the layer thickness-to-wavelength ratio e/λ for (a) a moderately pentrable layer, (b) a highly penetrable layer.

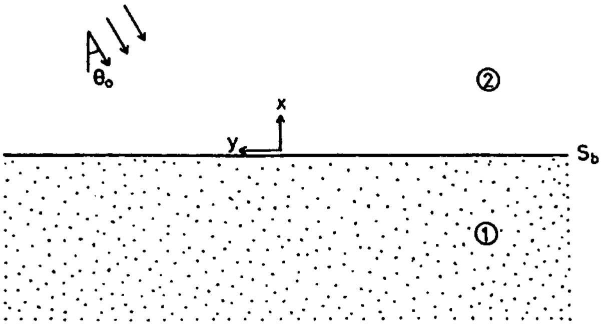

Fig. 4. Schematic diagram of plane acoustic wave acting on an infinitely thick poroelastic layer.

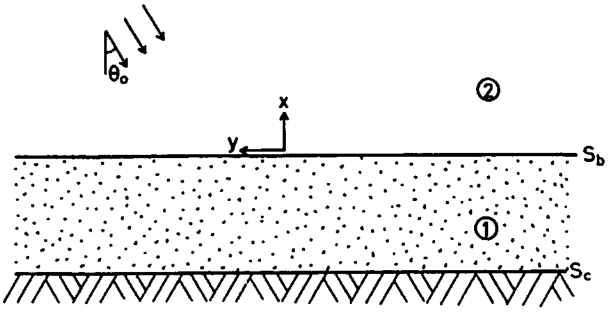

Fig. 5. Schematic diagram of a plane acoustic wave acting on a finite thickness poroelastic layer.

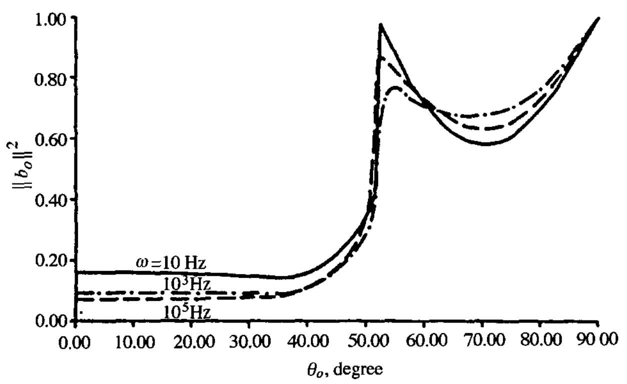

Fig. 6. Reflected acoustic intensities with respect to incident angles for a half-space seafloor.

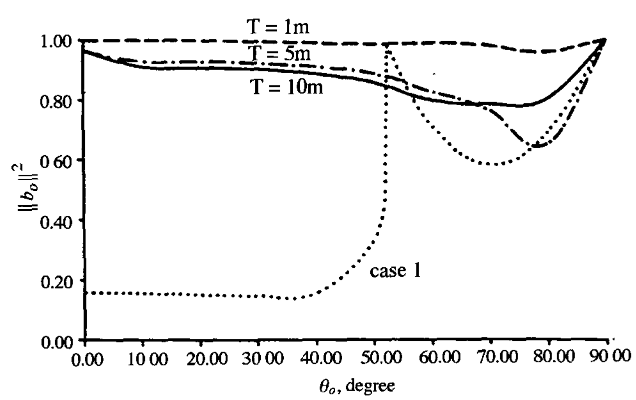

Fig. 7. Reflected acoustic intensities with respect to incident angles for ω=10 Hz and a finite thickness seafloor layer.

were studied by Huang (1992). Three frequencies of sound waves, 10 Hz, 10^3 Hz and 10^5 Hz, representing low, moderate, and high frequencies, respectively, a typical seafloor material, and incident angles from 0° to 90° were used in the analysis. A decoupling procedure of Biot's equations of poroelasitity for oscillatory motion, which divides the perturbation in the poroelastic medium into two longitudinal waves and one transvers wave, was applied. The reflected acoustic intensities for a porous seafloor of both infinite and finite thickness (Figs. 6-8) and the pressure-influence layers inside an infinite thickness porous seafloor were presented by Huang (1992). It was found that when the incident angle was larger than a certain value, it was possible to obtain the exact internal reflection for the first longitudinal wave.

The result of Huang (1992), especially the reflection coefficient b_0, e.g., the one for an infinite porous seafloor

$$b_0=\{-1+[(I1)(H2)-(I2)(H1)]2\cos\theta_0\frac{N}{M}\}L, \quad \textbf{(18)}$$

where

$$L=\frac{P_0}{\rho_0 C^2}, \quad \textbf{(19)}$$

$$N=\frac{K}{\rho_0 C^2 n_o}, \quad \textbf{(20)}$$

$$Hj=2\cos^2\theta_j+\frac{\lambda}{G}+\tan 2\theta_3 \sin 2\theta_j,\ j=1,\ 2, \quad \textbf{(21)}$$

$$Ij=1-(1-\alpha_j)n_0,\ j=1,\ 2,\ 3, \quad \textbf{(22)}$$

$$M=(I1)(H2)(J1)-(I2)(H1)(J2)$$
$$+(I3)(\sin 2\theta_1 H2-\sin 2\theta_2 H1)$$
$$\frac{k_0}{k_3}\frac{\sin\theta_3}{\cos 2\theta_3}, \quad \textbf{(23)}$$

$$Jj=\cos\theta_j\frac{k_0}{k_j}+\cos\theta_0 N,\ j=1,\ 2, \quad \textbf{(24)}$$

with notations used by Huang (1992), can be used in many other investigations.

Indeed, by applying Eq. (18), Chen and Huang (1992) analyzed a periodic acoustic point source in a shallow sea affected by a free surface and seafloor (Fig.

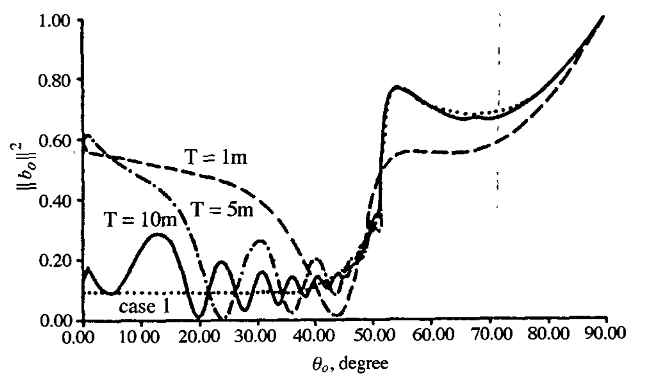

Fig. 8. Reflected acoustic intensities with respect to incident angles for ω=10^3 Hz and a finite thickness seafloor layer.

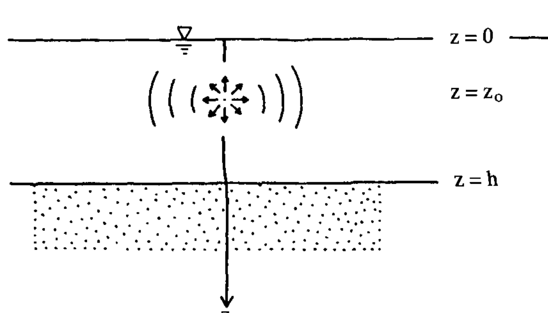

Fig. 9. Schematic diagram of an acoustic point source affected by a free surface and a falt seafloor.

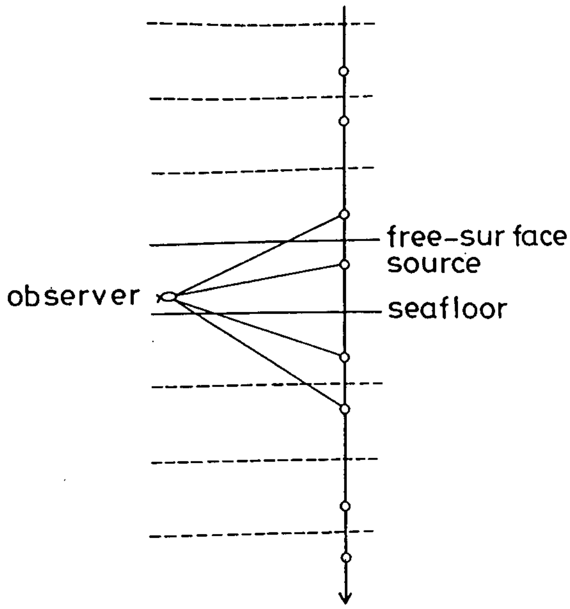

Fig. 10. Schematic diagram of the images of a point source in a layer of fluid.

9). Sea water was treated as a slightly compressible homogeneous inviscid fluid, and the material of the seafloor was assumed to be poroelastic. The solution to this problem was represented as an integration of plane wave expansion of the point source multipling the plane reflection coefficients of the boundaries. In this study, an asymptotic solution for this integration obtained by the method of steepest descent was adapted. Furthermore, the plane wave reflection coefficient of the seafloor found by Huang (1992) and an idealized plane reflection coefficient of the free surface were applied to the method of successive images (Fig. 10). Pressure amplitude distributions for different seafloor materials were presented as shown in Fig. 11. It was found that different assumptions of seafloor materials gave very different solutions of acoustic waves in layered sea water.

III. Rigid Screens

In the study of Huang and Chwang (1990a), a confocal rigid porous screen was held at a distance from a sphere (Fig. 12). Acoustic waves produced by the surface vibration of the spherical surface in an arbitrary pattern and the scattering of an incoming plane wave by the screened sphere were analyzed. The acoustic power far away from the screened sphere was compared to that associated with a sphere without a screen.

Figure 13 shows the relative radiation acoustic power F_{10}^R versus the gap-to-wavelength ratio d/λ at three fixed values porous Reynolds numbers,

$$Re = \frac{\rho_0 k\omega}{F(\kappa)\mu}, \tag{25}$$

Re=0.1, 1, and 10, for a single mode vibration. It is clear that Re controls only the amplitude. As r_b/λ approaches infinity, F_{10}^R becomes a periodic function of d/λ, independent of the vibrating mode and with a period of 1/2. For fixed values of r_b/λ, F_{10}^R becomes a periodic function of d/λ as d/λ becomes very large.

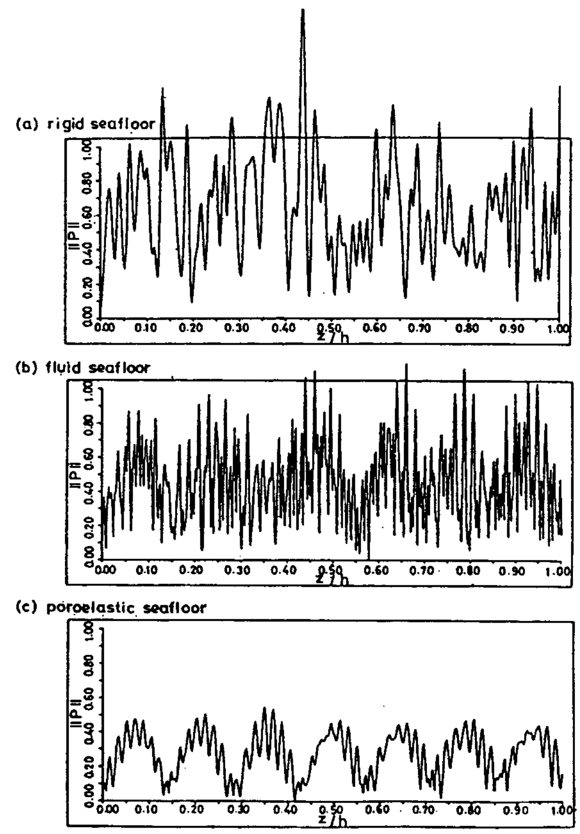

Fig. 11. Vertical pressure amplitude distributions, ω=10^3 Hz, r=$5h$, (a) rigid seafloor, (b) fluid seafloor, (c) poroelastic seafloor.

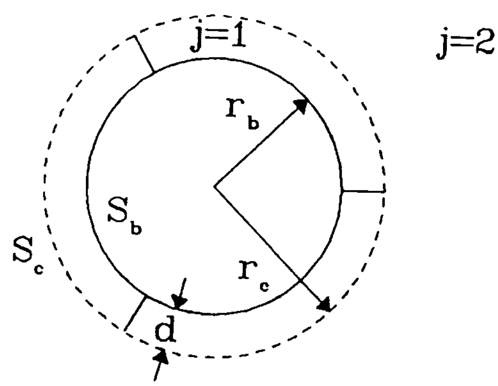

Fig. 12. Schematic diagram of a sphere covered by a concentric porous screen at a fixed distance.

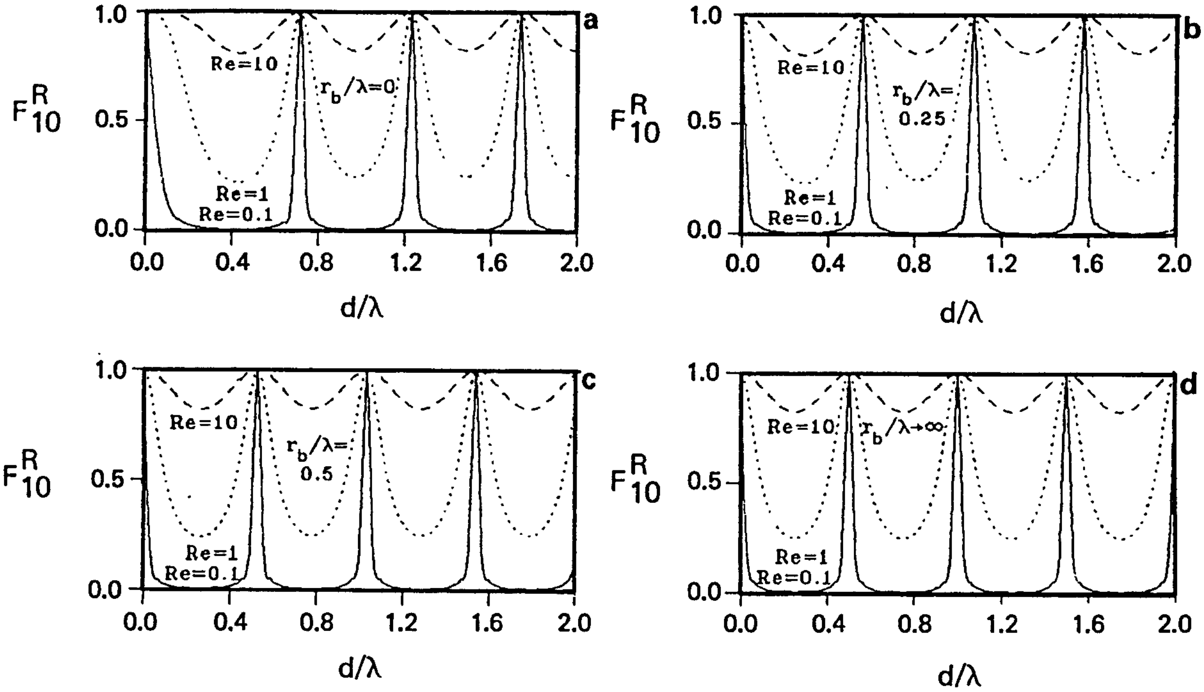

Fig. 13. Relative radition acoustic power F_{10}^{R} versus the gap-to-wavelength ratio d/λ for the pulsational mode (n=0) at fixed values of the Reynolds number Re with (a) r_b/λ=0, (b) r_b/λ=1/4, (c) r_b/λ=1/2, and (d) $r_b/\lambda \to \infty$.

We note that for fixed values of r_b/λ, F_{10}^{R} attains its maximum values at certain values of d/λ regardless of the value of Re.

Figure 14 shows the relative scattering acoustic power F_{10}^{S} versus d/λ and Re, respectively, for the limiting case of $k_0 r_b \to \infty$ and $d << r_b$. We note that in this limiting case, there is an optimum value of Re, Re=1, at which the relative acoustic power is a minimum, and that the absolute minimum value of F_{10}^{S} is 1/2, which occurs at d/λ=1/4+m/2 (m=0, 1, 2, ...).

The above analytical results for single-mode vibrations indicate that a screen is a good device for trapping and absorbing sound-wave radition. For a given frequency of sound waves, we can determine the best gap distance between the screen and the vibrating surface in order to minimize the relative acoustic power at infinity. On the other hand, for scattering of an incident plane wave by a screened sphere, the acoustic power with a screen may be higher than that without a screen. This is due to the extra reflection from the screen, which only exists with a screen.

Huang and Song (1993b) gave a rigorous derivation of the interaction of acoustic waves and a rigid screen based on a modification of Biot's theory of poroelasticity instead of physical intuition. A very easy and useful boundary condition for solving problems of noise in air passing through a moving rigid screen was, therefore, established. The boundary condition be-

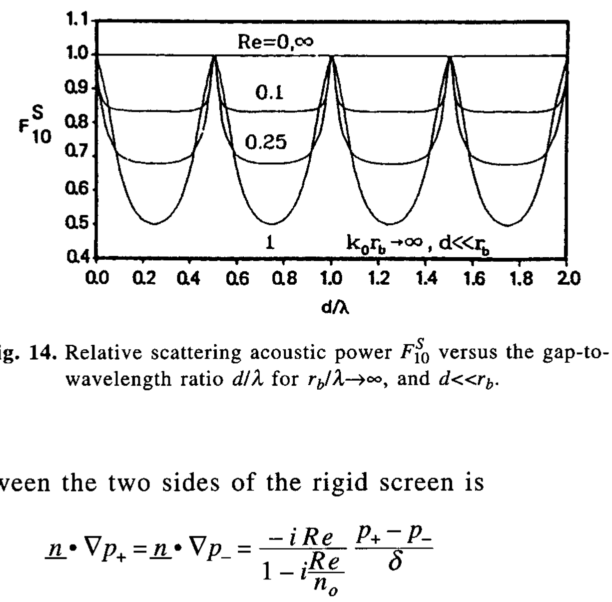

Fig. 14. Relative scattering acoustic power F_{10}^{S} versus the gap-to-wavelength ratio d/λ for $r_b/\lambda \to \infty$, and $d << r_b$.

tween the two sides of the rigid screen is

$$\underline{n} \cdot \nabla p_+ = \underline{n} \cdot \nabla p_- = \frac{-iRe}{1 - i\frac{Re}{n_o}} \frac{p_+ - p_-}{\delta} + \left(1 + \frac{iRe}{1 - i\frac{Re}{n_o}}\right) \rho_0 k_0 c^2 M I_{d_o} \cdot \underline{n} \ , \tag{26}$$

where Re is the porous Reynolds number and M is the Mach number,

$$M = \frac{\omega d_o}{c} \ , \tag{27}$$

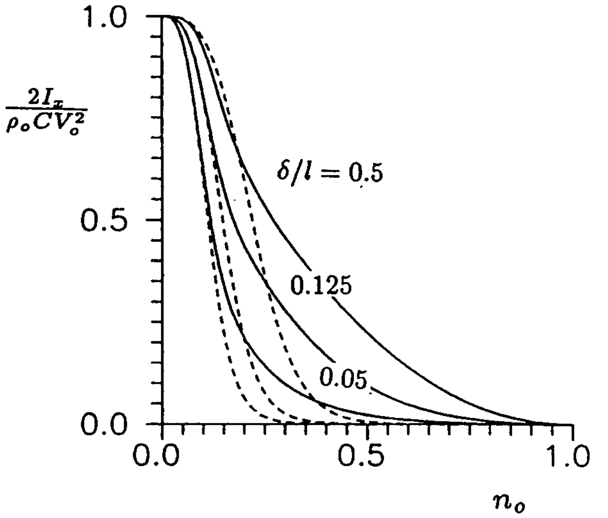

Fig. 15. The variation of the nondimensional acoustic intensity, $2I_x/\rho_o c V_o^2$, with respect to porosity, n_o, for different ratios of screen thickness to wavelength, δ/l. "——" with inertia, "-----" without inertia.

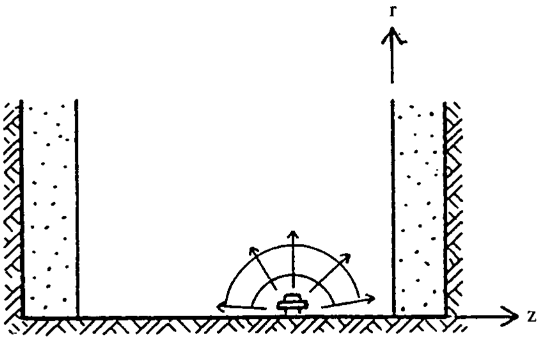

Fig. 16. Schematic diagram of transportation noise and noise barriers simulated by porous medium layers with rigid back walls.

and the other notations are those defined by Huang and Song (1993b).

An example of an oscillating plane rigid screen is shown in Fig. 15. Figure 15 shows the variation of the nondimensional acoustic intensity with respect to porosity for different ratios of screen thickness to wavelength. In Fig. 15, the solid lines are the results with inertia while the dotted lines are those without inertia. Figure 15 also shows that the inertial effect is significant and should be taken into account.

IV. Noise Barriers

Since the speed of a vehicle is much slower than the speed of sound, the linear problem of transportation noise acting on a noise barrier was simulated by Huang and Kung (1992a) using a still, single-frequency, and a three-dimensional sound source located within two parallel porous medium layers with rigid back walls (Fig. 16) and further simplified as a point source within two infinitely high walls (Fig. 17). On the other hand, a noise barrier simulated as porous screens with rigid back walls was given by Huang and Kung (1992b) (Figs. 18 and 19).

Huang and Kung (1992a, 1992b) expanded a three-dimensional point source by means of Fourier integral into a plane wave integration with respect to frequency:

$$\frac{e^{ik_oR_o}}{R_o} = \frac{ik_0}{2\pi}\int_0^{\frac{\pi}{2}-i\infty}\int_0^{2\pi} \exp[i(k_xx + k_yy \pm k_zz)] \sin\theta d\theta d\phi \ ,$$

$$\begin{cases} z \geq 0 \ , \\ z < 0 \ . \end{cases} \qquad (28)$$

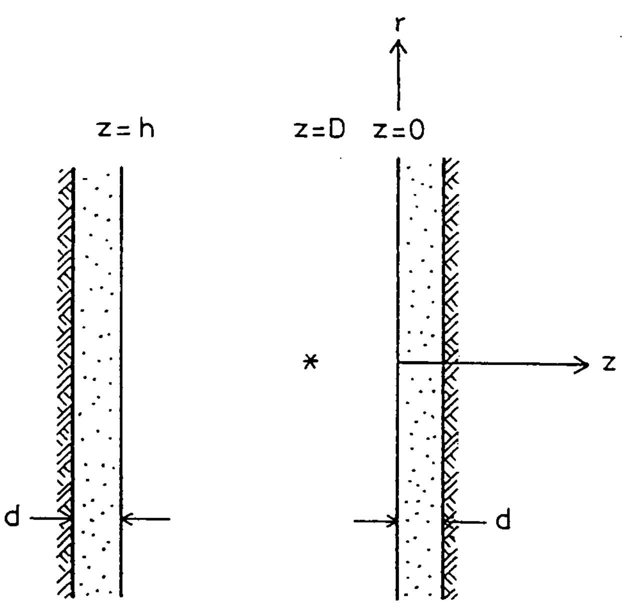

Fig. 17. Simulated diagram of transportation noise and noise barriers simulated by porous medium layers with rigid back walls.

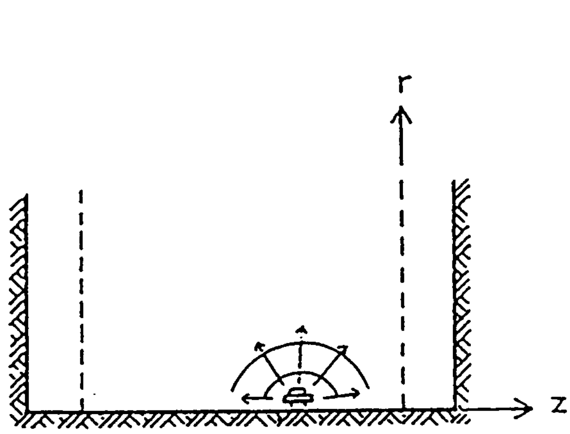

Fig. 18. Schematic diagram of transportation noise and noise barriers simulated by screens with rigid back walls.

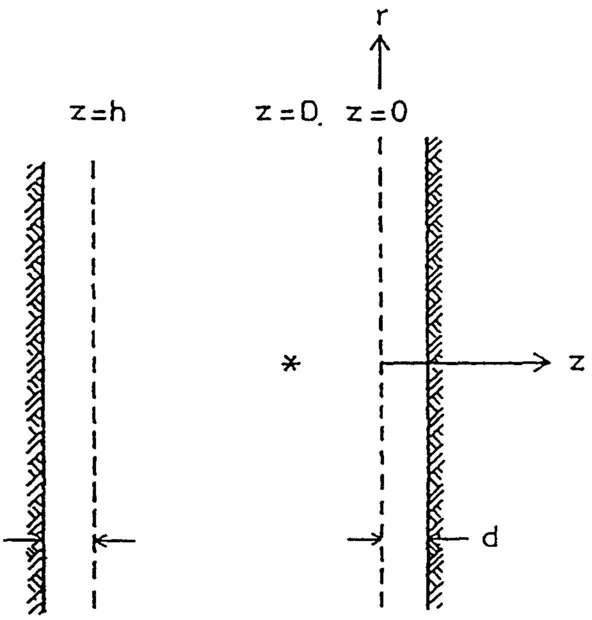

Fig. 19. Simulated diagram of transportation noise and noise barriers simulated by screens with rigid back walls.

where

$$R_o = \sqrt{r^2 + z^2}\ ,\ r^2 = x^2 + y^2, \tag{29}$$

and

$$k_x = k_o \sin\theta \cos\phi,\ k_y = k_o \sin\theta \sin\phi,\ k_z = k_o \cos\theta. \tag{30}$$

It was found that the solution of the reflection sound field of a noise barrier could be represented by an integration of this plane wave expansion of a point source with a proper reflection coefficient of the noise barrier multiplied in the integrand. Since the integral was still very complicated, the integrand was further converted into a function of incident angles and integrated with respect to incident angles. Finally, using the method of steepest descent and infinite images, the asymptotic solution of the reflected pressure was obtained as

$$P \sim \sum_{\ell=0}^{\infty} \sum_{j=1}^{4} P_{\ell j}\ , \tag{31}$$

where

$$P_{\ell j} = \frac{e^{ik_o R_{\ell j}}}{R_{\ell j}} \{ V_{\ell j}(\theta_{\ell j}) - \frac{i}{2k_o R_{\ell j}} [V''_{\ell j}(\theta_{\ell j}) + V'_{\ell j}(\theta_{\ell j}) \cot \theta_{\ell j}] \}\ , \tag{32}$$

$$R_{\ell j} = \sqrt{r^2 + z_{\ell j}^2}\ , \tag{33}$$

$$\theta_{\ell j} = \arctan\left(\frac{r}{z_{\ell j}}\right)\ , \tag{34}$$

with $V_{\ell j}$ as the reflection coefficient and

$$V_{\ell 1} = [V(\theta_{\ell 1})]^{2\ell}\ , \tag{35}$$

$$V_{\ell 2} = [V(\theta_{\ell 2})]^{2\ell+1}\ , \tag{36}$$

$$V_{\ell 3} = [V(\theta_{\ell 3})]^{2\ell+1}\ , \tag{37}$$

$$V_{\ell 4} = [V(\theta_{\ell 4})]^{2\ell+2}\ , \tag{38}$$

$$z_{\ell 1} = 2\ell h + z - z_o\ , \tag{39}$$

$$z_{\ell 2} = 2\ell h + z + z_o\ , \tag{40}$$

$$z_{\ell 3} = 2(\ell + 1)h - z - z_o\ , \tag{41}$$

$$z_{\ell 4} = 2(\ell + 1)h - z + z_o\ . \tag{42}$$

The asymptotic solution is the basis of the analysis presented in Huang and Kung (1992a, 1992b).

Based on the results of noise barrier simulations which they performed, Huang and Kung (1992a, 1992b) drew the following conclusions: (1) The width of the road has little effect on the noise barrier; therefore, the effect of the variation of the road width can be neglected in the design of a noise barrier. (2) A porous medium layered noise barrier is significantly affected by the viscous damping factor α while a screened noise barrier is significantly affected by the screen Reynolds number Re. It was found that in all cases, $\alpha = 1$ or $Re = 1$ gave the least road noise; therefore, it has the best sound trapping effect (for any given d). Also, the best gap-to-wave length ratio d/λ for the screen noise barrier is 1/4. (3) Because the decrease of sound intensity is very slow when r is large, increasing the height of the noise barrier in order to improve its noise control effect may not be economical.

A more reasonable diffracted sound field due to highway noise barriers was studied by Hsiao and Huang (1994) using the two-dimensional boundary integral element method. Six nodal points per wavelength and Gaussian quadruture integration with a second order Lagrange's interpolation function for each three-nodal-point element were suggested for the computation. By dividing the boundary acoustic impedance into two catagories, this work was able to handle problems with arbitrary acoustic impedance z.

The performance of noise barriers was judged based on the noise-blocking effect in the neighbouring areas of noise barriers. The variation of the material, the height h, and the shapes of the noise barriers were

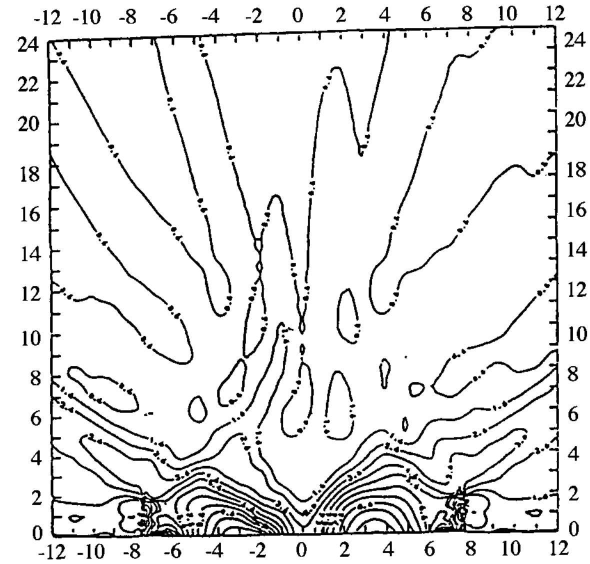

Fig. 20. Equal $||p||$ lines of a diffracted sound field due to noise barriers of $z \to \infty$, $h=2$ m.

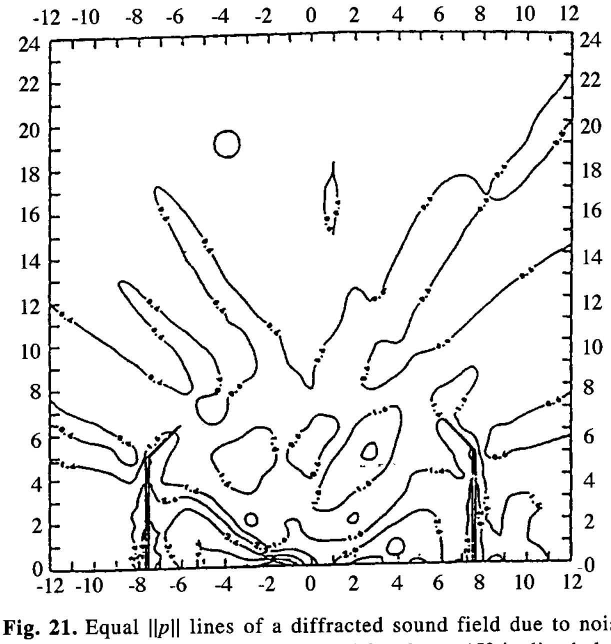

Fig. 21. Equal $||p||$ lines of a diffracted sound field due to noise barriers of $z \to \infty$, $h=5$ m, and 2 m long, 45° inclined slant plates.

discussed. It was concluded that only the shapes of noise barriers plays a key role in reducing noise in the neighbouring area while the material and the height of the barriers are not important. Figures 20 and 21 show contours of the diffracted sound fields of existing and suggested noise barriers, respectively. The shape effect of the noise barrier is demonstrated clearly by comparing these two figures.

V. Conclusions

Poroelastic media and rigid screens interacting with acoustic waves in a fluid are important subjects in marine geophysics, noise control etc. Not only the aforementioned noise barriers, but many other engineering applications can also be expected as a result of investigation in this field.

The interaction of porous solids with water waves is another interesting area worth studying. The design of a breakwater for coastal engineering relies heavily on this area's investigation. However, solutions to problems of seepage surface, fluid turbulence, etc. are still far from developed. Also, the use of porous media interacting with a fluid to simulate sediment transport might be an interesting new direction for research. Huang and Chiang (1995) reported some encouraging findings in this regard.

In summary, the study of the interaction between porous solids with a fluid still has a long way to go. The author hopes that the present introductory article will help stimulate many high quality works in this area in the near future.

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多孔固體與流體中聲波的互相作用

黃良雄

國立台灣大學土木工程學系暨水工試驗所

摘　要

本文回顧了流體中聲波與多孔固體互相作用的文獻。文中將作者與此主題相關之研究區分爲多孔彈性介質、剛性網、及隔音牆三類，並進行討論。作者報告了此三類研究之系列工作的摘要歸納及重要結果。