CHAPTER 24

BOTTOM DISSIPATION IN FINITE-DEPTH WATER WAVES

By

S. V. Hsiao[1] and O. H. Shemdin[2]

ABSTRACT

The dissipation of wave energy by various bottom mechanisms plays an important role in the spectral transformation of waves as they propagate from deep to shallow water. Three bottom dissipation mechanisms are discussed. The bottom friction mechanism is investigated in detail and a method for calculating the friction coefficient is proposed. The method is tested by comparison with field measurements. Dissipation due to percolation and bottom motion are also discussed. The magnitude of dissipation rates induced by the different mechanisms are compared under various wave and bottom conditions.

I. Introduction

The dissipation due to bottom friction is the work done by the wave orbital volocity against the bottom turbulent shear stress. The latter is usually expressed as

$$\vec{\tau} = \rho \ C_f \ |\vec{u}| \ \vec{u} \quad , \qquad (1)$$

where $\vec{\tau}$ is the turbulent shear stress, ρ is the density of water, C_f is the friction coefficient, and $\vec{u}$ is the velocity immediately outside the bottom boundary layer. Previous studies by Bretschneider and Reid (1954) and Hasselmann and Collins (1968) had indicated that the friction coefficient is of order 10^{-2}. Consequently, this value has been widely used. More recently, the friction coefficient has been observed to vary significantly above and below this value depending on the sand grain diameter and whether bottom ripples are present. This paper reviews the mechanisms responsible for generating bottom ripples and a method is proposed for estimating bottom friction coefficients under various bottom configurations.

The dissipation due to percolation is caused by viscous damping of energy induced by water seeping through the pores of the sandy bottom. Waves propagating above soft muddy bottoms can have their energy transferred at a rapid rate to the bottom mud layer where it is dissipated by the viscous motion induced in the bottom mud. The magnitude of such energy dissipation can be one to two oders of magnitude greater than that due to bottom friction or percolation. The rates of energy dissipation due to these three mechanisms are compared at corresponding water depths

[1]Scientist, Oceanography and Climate Group, Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California.
[2]Head of Oceanography and Climate Group, Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California and Professor, Department of Coastal and Oceanogrpahic Engineering, Univ. of Fla., Gainesville, Florida.

in the last section of this paper.

II. Review of Bottom Friction Studies

Bottom friction was first investigated by Putnam and Johnson (1949). They used the quadratic friction law, $\vec{\tau} = \rho\ C_f\ |\vec{u}|\ \vec{u}$, and found the dissipation rate for sinusoidal waves to be

$$\frac{1}{E}\frac{dE}{dt} = -\frac{4}{3}\frac{C_f\ \omega^3\ H}{g\ \sinh^3\ kh}, \qquad (2)$$

where E is wave energy, t is time, ω is wave frequency, H is wave height, k is wave number, and h is water depth. Bretschneider and Reid (1954) applied Putnam and Johnson's equation and found $C_f = 0.01$ for the sandy bottoms of the Gulf of Mexico. Hasselmann and Collins (1968) assumed the wave field to be Gaussian. They derived the following equation to compute the rate of energy dissipation in a random sea

$$\frac{1}{F(\vec{k})}\ \frac{d\ F(\vec{k})}{dt} = -\frac{g\ C_f\ k_i\ k_j}{\omega^2\ \cosh^2\ kh}\ (\delta_{ij} < |\vec{u}| > + < \frac{u_i\ u_j}{|\vec{u}|} >), \qquad (3)$$

where $F(\vec{k})$ is the wave energy density at wave number $\vec{k}$, < > denotes the ensemble average, i, j = 1, 2, u_1 and u_2 are the two orthogonal components of $\vec{u}$, k_1 and k_2 are the two corresponding wave number components of $\vec{k}$. They found C_f to be 0.015 using the wave spectra measured offshore of Panama City, Florida. Based on these two studies C_f values of the order 10^{-2} have been widely used (see for example Collins (1972) and U.S. Army Coastal Engineering Research Center (1973)). More recently, much higher values have been reported. Van Ieperen (1975) computed the friction coefficients for wave data obtained offshore of Melkbosstrand, South Africa to be in the range 0.06 - 0.10.

Laboratory and semi-theoretical studies by Jonsson (1965) indicate that C_f is a function of both the wave Reynolds number defined, $R = a\ U_m/\nu$, and the relative roughness defined, a/k_s, where a is one half of the horizontal orbital excursion above the bed, U_m is the maximum wave orbital velocity outside the bottom boundary layer, ν is the kinematic viscosity of water, and k_s is the bottom roughness. A friction factor diagram showing the relationship between the friction coefficient, the wave Reynolds number, and the relative roughness was first proposed by Jonsson (1965) based on very little data. Expanding the data base through a series of laboratory tests, Kamphuis (1975) presented his friction coefficient diagram shown in Figure 1 which shows that the friction coefficient can easily vary by one order of magnitude either above or below the widely used value of 10^{-2} depending on bottom roughness.

When sand ripples are formed on a sandy bottom, the bottom dissipation is enhanced due to form drag. Additional energy dissipation occurs in the vortices formed above the ripple troughs. The formation

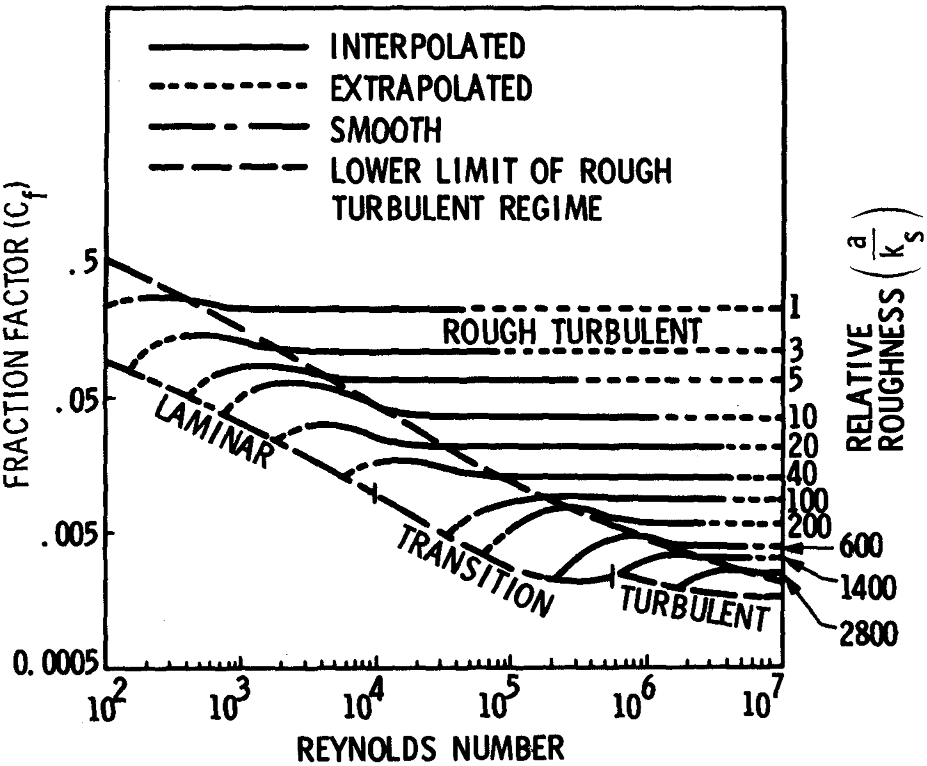

Figure 1. Friction factor diagrams (after Kamphuis, 1975).

of ripples has been investigated extensively in the laboratory, and to a lesser extent in the field. A review of these studies was reported by Dingler (1975) who also formulated a relationship for the prediction of bottom sand movement under wave action. The condition for the onset of sand motion suggested by Dingler (1975) has the form

$$\frac{\gamma_s T^2}{\rho D_s} = 240 \left(\frac{2a}{D_s}\right)^{4/3} \left(\frac{\rho\ \gamma_s\ D_s^3}{\mu 2}\right)^{-1/9} , \tag{4}$$

where $\gamma_s = (\rho_s - \rho)\ g$, ρ_s is the density of sand, T is wave period, D_s is the mean sand diameter, and μ is the viscosity of water. If this condition is satisfied, bottom ripples can be expected. The ripple slopes, ζ/λ_s, were found to have a functional dependence on a dimensionless stress parameter, θ_s, defined in terms of wave orbital velocity and bottom sediment properties as follows:

$$\theta_s = \rho\ U_m^2/\gamma_s D_s , \tag{5}$$

(see Figure 2). The ripples were found to vanish for $\theta \geqslant 2.5 \times 10^{2}$.

A different characterization of ripple properties was reported by Nielsen (1977) who found the dimensionless ratio, λ_s/a, to be functionally dependent on U_m/w, where w is the fall velocity of sand. The experimental results supporting such a relationship are shown in Figure 3. From the results of Dingler and Nielsen, it is possible to determine whether ripples are present, and then to predict the lengths and heights of such ripples. The only necessary inputs are the properties of prevailing waves and bottom sediment. As will be shown in the following sections, the ripple heights determine the bottom roughness and consequently the magnitude of the friction coefficient.

III. A Proposed Method for Estimating the Bottom Friction Coefficient

From the discussion in section II, it is clear that a constant C_f value of 10^{-2} cannot be expected to be universally valid. In this section, a method for determining C_f is proposed.

In analogy with friction losses over rigid boundaries, the use of a friction diagram such as shown in Figure 1 is necessary to estimate C_f. For given wave and depth conditions, it is possible to determine the Reynolds number $R = U_m\ a/\nu$ and the orbital amplitude, a. Still, the roughness height, k_s, must be estimated before C_f is determined.

For a flat bottom, the roughness height, k_s, is assumed to be equal to the sediment diameter, D_s. Therefore, under conditions when Equation (4) can not be satisfied or $\theta \geqslant 2.5 \times 10^{2}$ the value of k_s is determined directly from D_s. Then C_f is defined from known value of (a/k_s) and R using Figure 1.

When the wave and bottom sediment conditions satisfy Equation (4), bottom ripples form. Their heights, ζ, and lengths, λ_s, are then determined in the manner discussed in section II. In the presence of ripples Tunstall and Inman (1975) found that the experimental results of Bagnold (1946), Inman and Bowen (1963), Jonsson (1966), Cartsens et al (1969), and Reidel et al (1972) all supported an inverse dependence of

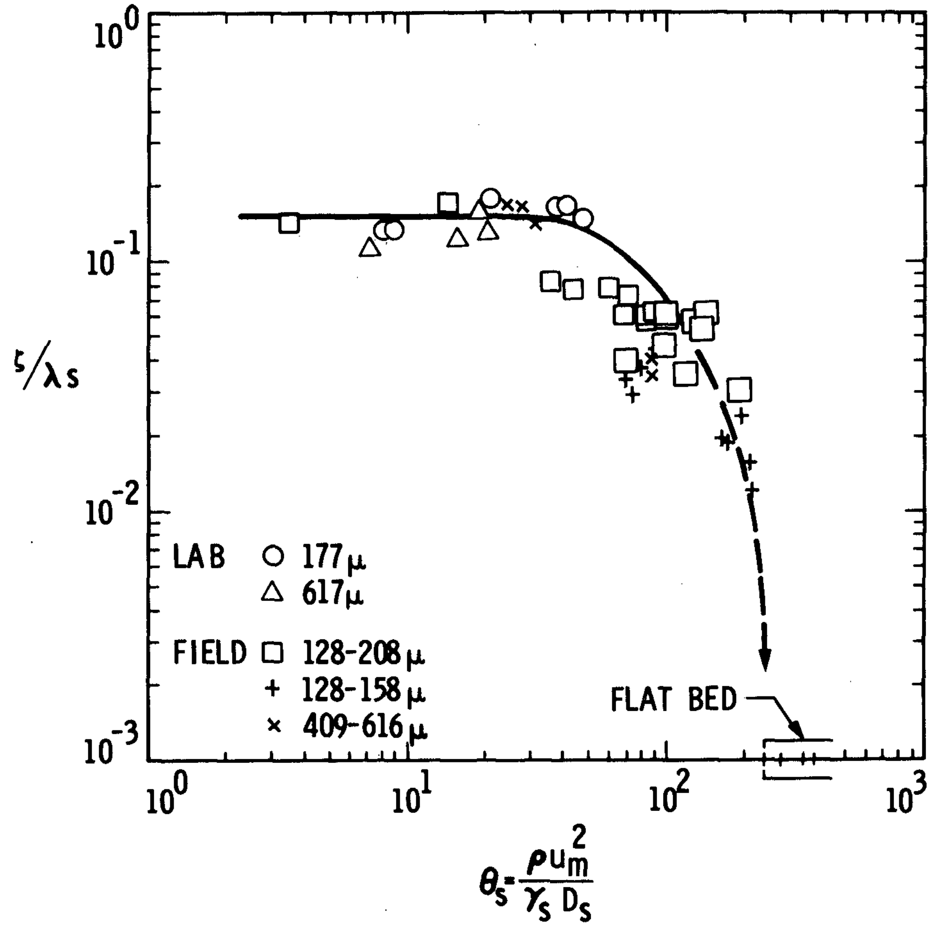

Figure 2. Ripple steepness vs. relative stress (after Dingler, 1975).

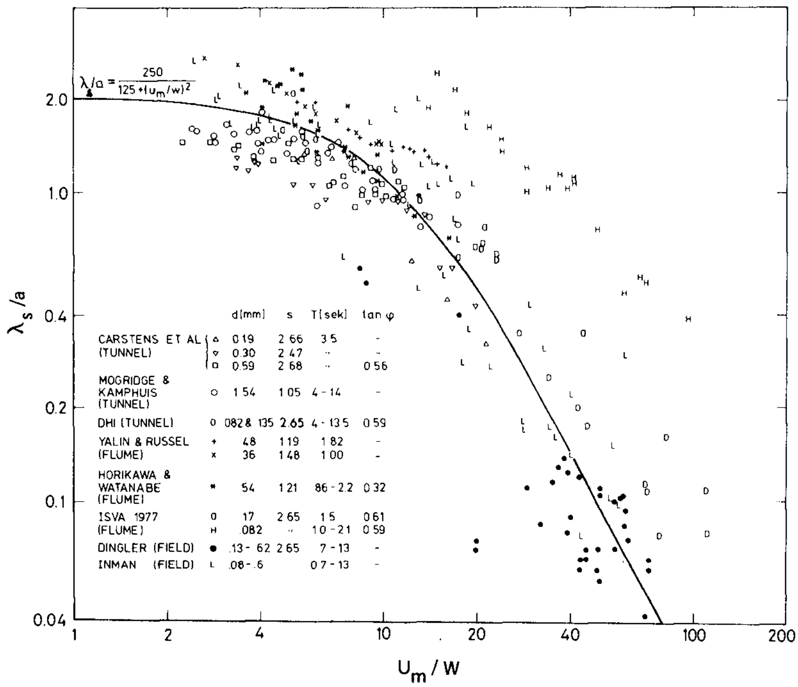

Figure 3. λ_s/a vs. U_m/w (after Nielsen, 1977).

C_f on (a/k_s) provided that $k_s = 4\zeta$. The friction coefficient diagram shown in Figure 1 is in fact constructed to provide the correct C_f value for a given R value. As ripples form, the k_s value increases in proportion to the ripple height, ζ, so that the ratio of (a/k_s) decreases. The latter increases C_f. In the following section the validity of this procedure is tested against new field data not used in deriving the friction diagram.

IV. Friction Coefficients Computed from Field Measurements

Two sets of wave date were available to compute the friction coefficients in order to verify the method described in section III. One is the wave spectra obtained offshore of Panama City, Florida on September 9, 1965 (Breeding , 1972). The waves were measured by two pressure sensor arrays located at 31.7 m and 19.2 m water depths. The other is the spectra obtained offshore of Marineland, Florida on December 14, 1975 (Shemdin et al, 1975). A Geodolite laser sensor was used to measure the waves at 31 m water depth and a pitch-and-roll buoy was used at 8.5 m water depth.

The C_f values were computed from spectra at two different depths using a method similar to that of Hasselmann and Collins (1968). For the Panama City case the C_f values were found to be in the range 0.035-0.05. A sample predicted shallow water spectrum is compared with the measured shallow water spectrum in Figure 4. The C_f value in this particular calculation is 0.04.

Using the method described in section III, the estimated C_f value is 0.03. It is also found to be approximately a constant between the two measuring stations based on wave and sediment conditions at both stations. A summary of wave and sediment conditions needed to calculate C_f is shown in Table 1. The agreement between the proposed procedure for calculating C_f and the values obtained from shoaling spectra is of order 25%. The agreement is considered reasonable.

For the Marineland data the computations are somewhat more complicated by the fact that conditions vary sufficiently between the two stations to warrant different bed forms and C_f values. From the measured wave spectra, a constant Cf value of 0.008 is computed. The procedure outlined in section III provide C_f estimates which vary from 0.05 at 30 m water depth to 0.002 at 8.5 m water depth. A summary of wave and sediment parameters is shown in Table 1. In order to test the validity of the procedure outlined in section III, predicted shallow water spectra are compared with measured shallow water spectra in Figure 5. The predicted spectra are based on (a) fixed $C_f = 0.008$, and (b) variable C_f from 0.05 in deep water to 0.002 in shallow water. At high frequencies the fixed and variable C_f values give similar results. At low frequencies the variable C_f value procedure gives better agreement with the measured values in shallow water. The Marineland data set serves to demonstrate that predicting shallow water waves may not be as simple as defining a representative value for the entire shoaling region and that more detailed measurements are needed to verify the procedure outlined in section III.

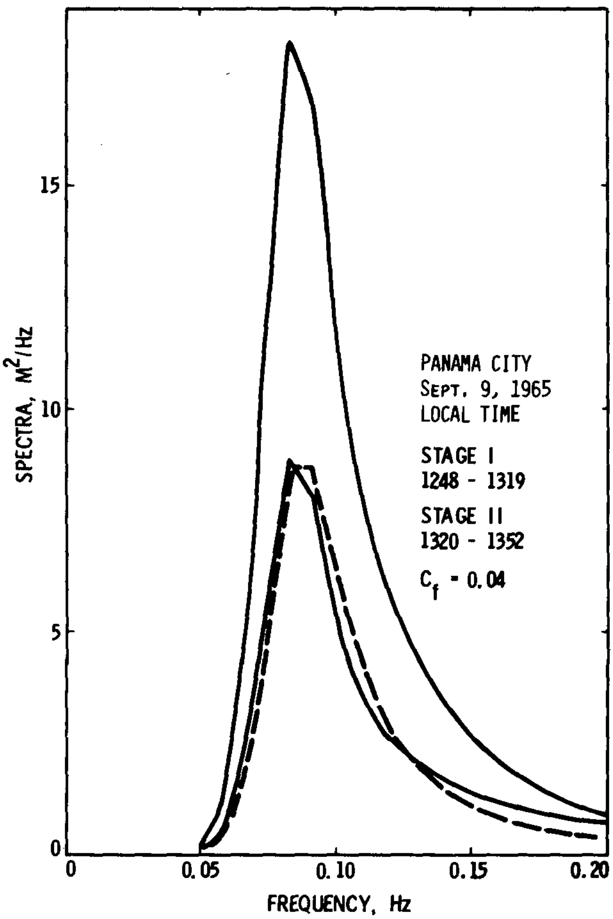

Figure 4. Comparison between measured and computed Panama City spectra. —— measured, – – computed at Stage II.

Table 1. Estimation of Friction Coefficients from Wave and Sand Parameters

Variable	Marineland		Panama City	South Africa (TBO 37)
h	30	8.5	19.2 - 31.7	10.6 - 32
T_m	8	8	12	13.7
$H_{1/3}$	1.7	1.5	1.9 - 3.7	2.3 - 2.8
d_o	0.49	1.68	1.9 - 2.9	2.6 - 4.5
D_s	(0.1×10^{-3})		(0.4×10^{-3})	(1.5×10^{-3})
λ	0.070	0.032	0.24	0.9
θ	24 -	290	33 - 82	15 - 45
ζ	0.012	0	0.024	0.15
k_s	0.048	0.0001	0.096	0.60
C_f	0.05	0.002	0.03	0.10

h = water depth (m)

T_m = peak period (sec)

$H_{1/3}$ = significant wave height (m)

d_o = horizontal excursion (m)

D_s = median sand diameter (m)

λ_s = ripple wave length (m)

θ_s = nondimensional relative stress

ζ = ripple wave height (m)

k_s = roughness height (m) (4ζ as was suggested by Jonsson, 1966)

C_f = friction coefficient

Finally, the procedure proposed in section III is tested by using it to estimate a C_f value for the waves measured offshore of Melkbosstrand, South Africa. The bottom sediment properties in that region were not reported. A value of $C_f = 0.1$, in agreement with that calculated from shoaling spectra, could only be predicted if the bottom material was composed of coarse sand with $D_s = 1.5$ mm. Under such conditions bottom ripples can form and the high reported C_f values can be explained. A summary of wave and assumed sediment conditions for Melkbosstrand is also included in Table 1.

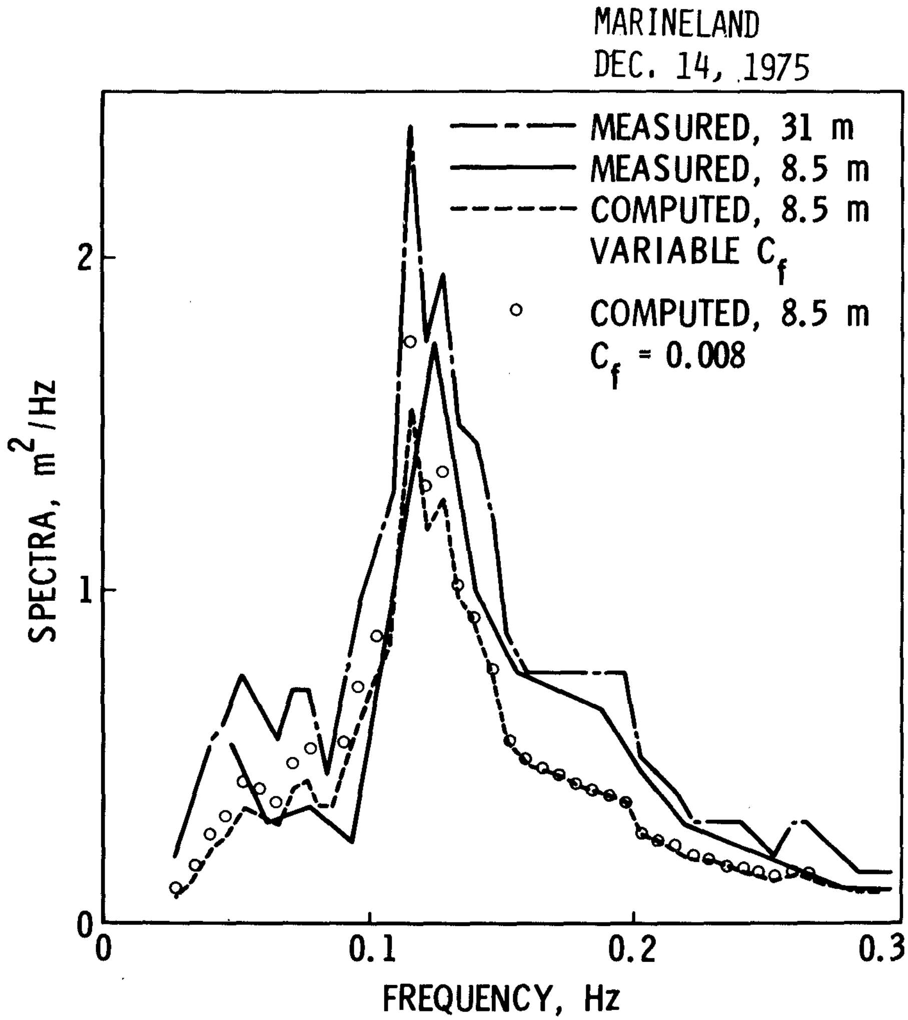

Figure 5. Comparison between measured and computed Marineland wave spectra.

V. Percolation Dissipation

Putnam (1949) was the first to compute the wave energy dissipation rate due to percolation in an isotropic permeable sandy bottom. However, he overestimated the dissipation rate by a factor of four due to an arithmetic error. Later, Bretschneider and Reid (1954) applied Putman's equation to study the wave height modification and consequently overestimated the percolation damping. A more general equation to compute the percolation dissipation rate was given by Shemdin et al (1977) as

$$\frac{1}{E}\frac{dE}{dt} = - k \sqrt{\alpha\beta} \; \frac{\tanh \sqrt{\frac{\alpha}{\beta}}\, kd}{\cosh^2 kh} \quad , \tag{5}$$

where α and β are the horizontal and vertical coefficients of permeability, respectively, and d is the thickness of the sand layer. Using this equation and the magnitude of permeability coefficients determined by Sleath (1970) they computed the dissipation rates at different water depths. The results are compared with corresponding friction dissipations in Figure 6. These results demonstrate that percolation dissipation can be more important than friction dissipation for coarse sand in deeper water.

VI. Bottom Motion Dissipation

Excessive attenuation of wave energy in the Mississippi Delta area was reported by Bea (1974) and Tubman and Suhayda (1976). The attenuation cannot be reasonably explained by refraction, shoaling, bottom friction, nor bottom percolation. It is believed that the excessive attenuation is due to the effect of the wave-induced motion in the soft muddy bottom. Gade (1958, 1959) studied the wave enery dissipation effects of a non-rigid bottom in shallow water. His results are restricted to only shallow water waves. (i,e,$kh < 0.1\,\pi$) and cannot be applied to intermediate waver waves. Mallard and Dalrymple (1977) studied the effects of an ideal elastic bottom on water waves. Their computations, which neglected viscosity in the mud, show no wave energy loss. Hsiao and Shemdin (1978) assumed a viscoelastic bottom and obtained the following dispersion equation

$$k = \frac{\omega^2}{g} \; \frac{1 + \tanh kh\, \Omega}{\tanh kh + \Omega} \tag{6}$$

where Ω is a function of wave and bottom properties and k is the complex wave number in which the imaginary part is a measure of energy dissipation. The dissipation rates predicted by Equation (6) can explain the wave decay rates reported by Tubman and Suhayda (1976). Some computed dissipation rates using Equation (6) are shown in Figure 6 for comparison with dissipation rates due to friction and percolation. It can be clearly seen that the dissipation rate due to bottom motion can be one to two orders of magnitude greater than those due to friction and/or percolation.

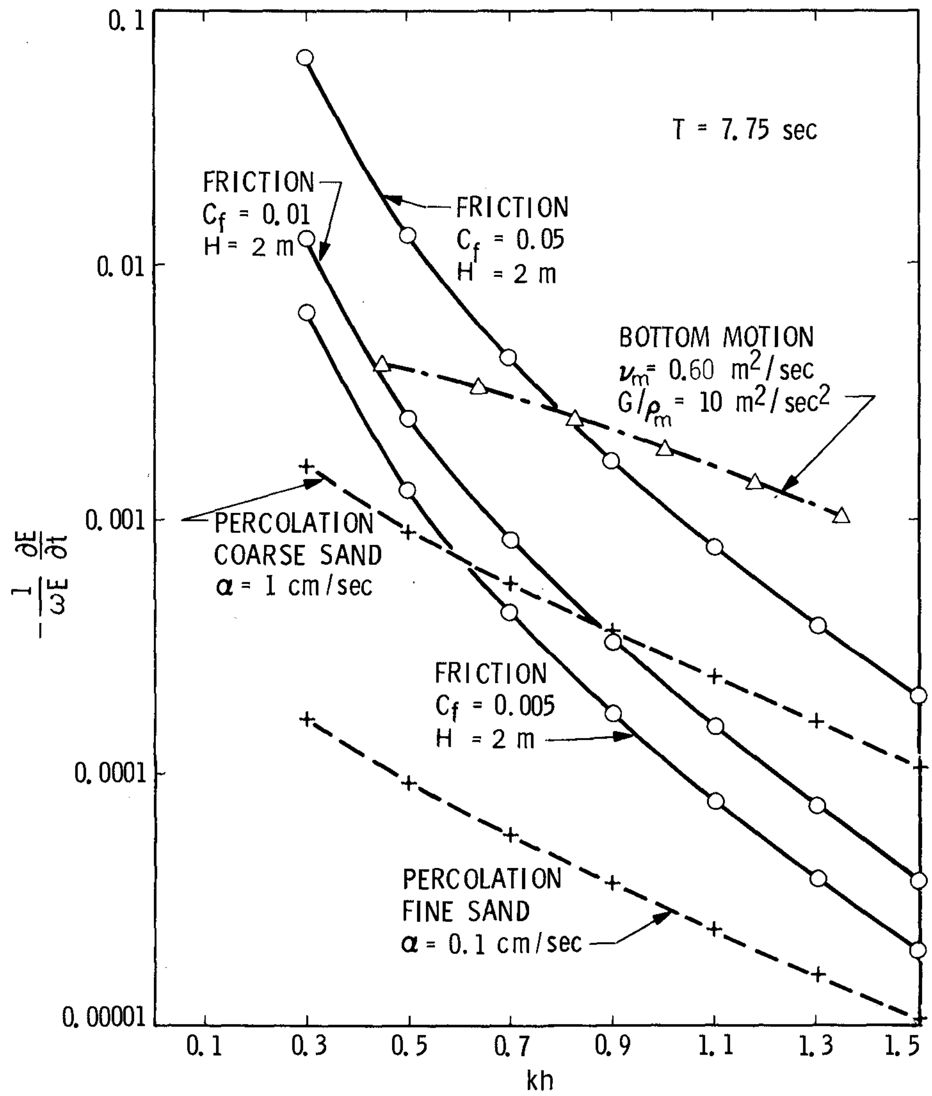

Figure 6. Comparison between dissipation mechanisms. ν_m = kinematic viscosity of mud, G = shear modulus of mud, ρ_m = density of mud (after Shemdin et al, 1977).

VII. Conclusions

It is shown that any of the three dissipation mechanisms discussed in this paper, namely friction, percolation, and bottom motion can be dominant in dissipating wave energy in shallow water depending on wave properties and bottom sediment properties. None can be arbitrarly neglected. Information on bottom sediment is considered of critical importance to properly identify the prevailing mechanism. Such information is not routinely obtained when measuring shoalling waves.

The friction coefficient is found to vary considerably above or below the widely used 10^{-2} value. A method for estimating the friction coefficeint is suggested and found to give acceptable values over a broad range of conditions.

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