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CRITICAL WAVE CONDITIONS FOR SAND MOTION INITIATION.(U)
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Critical Wave Conditions for Sand Motion Initiation.

by

Robert J. Hallermeier

COASTAL ENGINEERING TECHNICAL AID NO. 81-10

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Sand and fluid characteristics together with the period of oscillatory flow determine the peak fluid velocity needed for sand motion initiation. With linear wave theory, this threshold peak near-bottom velocity can be used to calculate critical wave conditions for sand motion--either the minimum wave height in a given water depth, or the maximum water depth with a given wave height, for a given wave period. The procedure presented here permits prediction of the seaward extent of bed activity due to wave action in field and laboratory situations. Example calculations are provided.

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PREFACE

This report provides a calculation procedure for the threshold of sand motion by wave action, and thus, an ultimate seaward limit to wave effects on a sand bottom. The present treatment replaces guidance on initiation of sediment motion furnished in Section 4.522 of the Shore Protection Manual. The work was carried out under the beach behavior and restoration research program of the U.S. Army Coastal Engineering Research Center (CERC).

This report was written by Dr. Robert J. Hallermeier, Oceanographer, under the general supervision of Dr. R.M. Sorensen, Chief, Coastal Processes and Structures Branch, Research Division.

Comments on this publication are invited.

Approved for publication in accordance with Public Law 166, 79th Congress, approved 31 July 1945, as supplemented by Public Law 172, 88th Congress, approved 7 November 1963.

TED E. BISHOP
Colonel, Corps of Engineers
Commander and Director

CONTENTS

CONVERSION FACTORS, U.S. CUSTOMARY TO METRIC (SI) UNITS OF MEASUREMENT

U.S. customary units of measurement used in this report can be converted to metric (SI) units as follows:

Multiply	by	To obtain
inches	25.4	millimeters
	2.54	centimeters
square inches	6.452	square centimeters
cubic inches	16.39	cubic centimeters
feet	30.48	centimeters
	0.3048	meters
square feet	0.0929	square meters
cubic feet	0.0283	cubic meters
yards	0.9144	meters
square yards	0.836	square meters
cubic yards	0.7646	cubic meters
miles	1.6093	kilometers
square miles	259.0	hectares
knots	1.852	kilometers per hour
acres	0.4047	hectares
foot-pounds	1.3558	newton meters
millibars	1.0197×10^{-3}	kilograms per square centimeter
ounces	28.35	grams
pounds	453.6	grams
	0.4536	kilograms
ton, long	1.0160	metric tons
ton, short	0.9072	metric tons
degrees (angle)	0.01745	radians
Fahrenheit degrees	5/9	Celsius degrees or Kelvins[1]

[1]To obtain Celsius (C) temperature readings from Fahrenheit (F) readings, use formula: $C = (5/9)(F - 32)$.
To obtain Kelvin (K) readings, use formula: $K = (5/9)(F - 32) + 273.15$.

SYMBOLS AND DEFINITIONS

D	median sand-grain diameter
d	mean water depth
d_{max}	maximum water depth for sand motion with given wave height and period
g	acceleration due to gravity
H	wave height
H_{min}	minimum wave height for sand motion with given depth and wave period
L	linear wavelength for given depth and wave period
m	subscript denoting critical velocity with vigorous near-bed mixing
$S = HL^2/2d^3$	Stokes parameter measuring wave nonlinearity
T	wave period $= \frac{2\pi}{\omega}$
t	subscript denoting transitional critical velocity
$u_{max(-d)}$	maximum linear wave-induced horizontal velocity near the bed
v	subscript denoting critical velocity with viscous near-bed layer
$\gamma' = (\rho_s - \rho)/\rho$	normalized immersed sediment density
δ	weighting factor
ε	weighting factor
ν	kinematic fluid viscosity
ξ	horizontal amplitude of near-bed fluid orbit
ρ	fluid mass density
ρ_s	sediment mass density
ω	angular wave frequency

CRITICAL WAVE CONDITIONS FOR SAND MOTION INITIATION

by
Robert J. Hallermeier

I. INTRODUCTION

Various engineering activities require consideration of the seaward limit for significant bed activity caused by surface waves. Sometimes the ultimate seaward limit to bed activity by waves is of interest; examples include field borrow of inactive sand for beach nourishment, and design of laboratory tests to include the entire active nearshore region. The ultimate seaward limit to wave-induced bed activity can be defined using a criterion for sediment motion initiation by oscillatory flow.

This report provides a procedure for calculating critical conditions for wave-induced motion of sand grains (median sediment diameter, D, between 0.06 and 2.0 millimeters), based on the motion initiation criterion for a level bed established by Hallermeier (1980). That report reviews the available experimental data and concludes that the criterion used here is simpler and more reliable in predicting oscillatory-flow initiation of sand motion than the well-known Shields criterion. The present criterion is also an improvement on the somewhat qualitative guidance presented in Section 4.522 of the Shore Protection Manual (SPM) (U.S. Army, Corps of Engineers, Coastal Engineering Research Center, 1977).

Section II presents this criterion by giving the threshold flow velocity for sand motion in terms of sand and fluid characteristics and the flow period. Relationships for linear waves are provided to permit conversion of this peak near-bottom velocity into critical wave conditions for sand motion--either a minimum wave height with a given water depth, or a maximum water depth with a given wave height. Possible effects of physical factors ignored in this calculation procedure are also discussed.

Section III provides example calculations of critical conditions for sand motion using the equations and graphical relationships presented in this report.

II. THE CALCULATION PROCEDURE

1. Threshold Velocity for Sand Motion Initiation.

Using empirical results, two approximate asymptotic forms can be identified for motion initiation on a level sand bed, and these forms permit a simple prediction procedure for sand motion using physical values which are usually specifiable. These asymptotic forms for motion initiation correspond to viscous near-bed effects being either dominant or negligible. The five values to be specified for a calculation are:

D = median sand-grain diameter;

ω = the oscillatory-flow frequency = $(2\pi/T)$, where T is flow period;

γ' = $(\rho_s-\rho)/\rho$, where ρ_s is sediment mass density and ρ is fluid mass density;

g = acceleration due to gravity;

ν = kinematic fluid viscosity.

For convenience, a Table lists usual values of ρ_g, ρ, g, and ν.

Table. Values for material characteristics used in calculations.

Characteristic	Values		
Sediment mass density, ρ_g	Quartz:	5.14 slugs/ft^3 (2.653 gm/cm^3)	
	Calcite:	5.26 slugs/ft^3 (2.711 gm/cm^3)	
Fluid mass density, ρ	Freshwater:	1.94 slugs/ft^3 or 0.998 gm/cm^3 (20°C, 1 atmosphere pressure)	
	Saltwater:	1.99 slugs/ft^3 or 1.026 gm/cm^3 (35 °/.. salinity; 15°C, 1 atmosphere pressure)	
Acceleration due to gravity, g	Standard:	32.2 ft (981 cm)/s^2	
		ft^2/s	cm^2/s
Kinematic fluid viscosity, ν	Freshwater: 5°C:	1.64×10^{-5}	0.0152
	10°C:	1.41×10^{-5}	0.0131
	15°C:	1.23×10^{-5}	0.0114
	20°C:	1.08×10^{-5}	0.0100
	25°C:	0.96×10^{-5}	0.0089
	30°C:	0.86×10^{-5}	0.0080
	Saltwater: (35 °/..) 5°C:	1.69×10^{-5}	0.0157
	10°C:	1.45×10^{-5}	0.0135
	15°C:	1.28×10^{-5}	0.0119
	20°C:	1.13×10^{-5}	0.0105
	25°C:	1.01×10^{-5}	0.0094

With these five values specified, sand motion initiation occurs at a predictable threshold near-bed fluid velocity, $(\xi\omega)$, where ξ, the horizontal amplitude of the near-bed fluid excursion, is the single unknown. The condition for motion with viscous effects dominant near the sand bed is

$$(\xi\omega)_v = \frac{0.35\ D^{0.25}(\gamma' g)^{0.75}}{\omega^{0.5}} \qquad (1)$$

applicable for $D \leq 0.07$ centimeter and $(\xi\omega)_v < 1.15$ feet (35 centimeters) per second, according to empirical results. The condition for motion with viscous effects negligible (due to a thoroughly mixed rather than laminar boundary layer) is

$$(\xi\omega)_m = (8\ \gamma' g D)^{0.5} \qquad (2)$$

Equation (2) is applicable for $\varepsilon \geq 1$,

where

$$\varepsilon = \frac{(\xi\omega)_m \, D^{0.29}}{266.5 \, \omega^{0.355} \, \nu^{0.645}} \tag{3}$$

describes the state of near-bed mixing due to sediment grain roughness.

Available evidence indicates that equation (2), which usually gives a lower velocity than equation (1), should always be applied in field situations due to the prevalence of nonlaminar flow. Equation (1) is usually applicable in laboratory situations with relatively high flow frequency and fine sand. In transitional laboratory situations where neither equation (1) nor equation (2) is definitely appropriate, the transitional condition for sand motion is

$$(\xi\omega)_t = \frac{\varepsilon^2(\xi\omega)_m + \delta^2(\xi\omega)_v}{\varepsilon^2 + \delta^2} \tag{4}$$

where one weighting factor is ε given by equation (3) and the other is

$$\delta = 2 - \frac{(\xi\omega)_v}{1.15} \quad [(\xi\omega)_v \text{ in ft/s}] \tag{5}$$

2. Conversion to Critical Linear Wave Conditions.

The threshold velocity given by equation (1), (2), or (4) can be converted to more generally useful critical wave conditions for sand motion using relationships from linear wave theory. Peak near-bottom horizontal fluid velocity induced by a linear surface wave is

$$u_{max(-d)} = \xi\omega = \frac{\omega H}{2 \sinh\left(\frac{2\pi d}{L}\right)} \tag{6}$$

where H is the surface wave height, d the local water depth, and L the local wavelength determined by

$$\frac{2\pi d}{L} \tanh\left(\frac{2\pi d}{L}\right) = \frac{\omega^2 d}{g} \tag{7}$$

The Figure provides graphs of (sinh x) and [x(tanh x)] as a function of x, which are needed with equations (6) and (7) and the critical velocity from equation (1), (2), or (4) to compute minimum wave height for sand motion in a given water depth, or maximum water depth for sand motion with a given wave height.

For the minimum wave height computation, the calculated $(\omega^2 d/g)$ is used as the ordinate of the [x(tanh x)] curve in the Figure to yield the value of the argument $x = (2\pi d/L)$ and of $\sinh(2\pi d/L)$. Equation (6) then gives the minimum wave height for sand motion, H_{min}, to be $[2(\xi\omega) \sinh(2\pi d/L)/\omega]$.

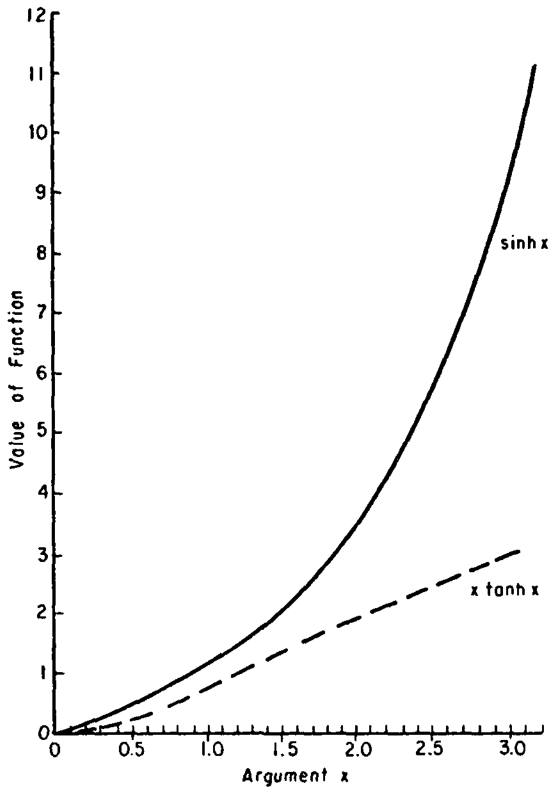

Figure. Graph of the functions, sinh x and x(tanh x).

For maximum water depth computation, the calculated $[\omega H/2(\xi\omega)]$ is used as the ordinate of the (sinh x) curve in the Figure to determine the value of the argument $x = (2\pi\ d/L)$. This permits finding the value of $[(2\pi\ d/L) \tanh (2\pi\ d/L)]$ in the Figure. According to equation (7), the last value multiplied by (g/ω^2) is the maximum water depth for sand motion, d_{max}.

3. Consideration of Other Physical Factors.

The calculation procedure presented above is based on a review of available laboratory results for sediment motion initiation by sinusoidal fluid flow over a leveled horizontal bed of well-sorted sand. This data base does not reflect effects of several physical factors potentially important in common situations, such as poorly sorted sands, bed forms, mean bed slope, wave height, frequency or direction spectrum, and any superimposed steady flow. Another possible limitation is that the linear theory is used for calculating wave characteristics, in particular, peak near-bottom fluid velocity. Some pertinent information on these assumptions and omissions is presented below.

a. Linear Wave Theory. Available information indicates that the linear wave theory accurately gives near-bottom velocity if

$$S = \frac{HL^2}{2d^3} \leq 8; \tag{8}$$

otherwise, surface waves have a nonsinusoidal profile and a calculation using linear wave theory may underestimate the actual peak near-bottom velocity. Using the values of (d/L) and (d/H) found in determining critical conditions, S can be conveniently calculated. If equation (8) is not satisfied, the calculated critical conditions must be regarded with appropriate caution. If the minimum wave height for sand motion in a given depth has been calculated, a somewhat smaller wave height might actually induce motion; if the maximum water depth for sand motion with a certain wave height has been calculated, sand motion might actually occur in a somewhat greater water depth.

b. Poorly Sorted Sand. If there is a wide range of grain sizes in a sediment sample, some evidence indicates that the effective grain size for consideration of sediment movement is smaller than the median sediment diameter, D, commonly taken to describe the sediment. No quantitative guidelines can be presented, but if the sand is judged to be poorly sorted (e.g., bimodal), calculations using D for critical conditions should be regarded with the same caution described above: the present procedure provides the minimum extent of bed activity for the specified wave condition.

c. Bed Forms. Sand motion initiation on a bed with previously fully grown vortex ripples can be caused by a peak velocity that is about 50 percent of that required on a level bed. Natural relict bed forms may not have this great an effect on the critical fluid velocity for sand motion, but the prevalence of relict bed forms in nature indicates that the present procedure provides the minimum extent of bed activity. Bed forms also contribute to disorder in the near-bottom boundary layer, which suggests that the motion criterion of equation (2), rather than equation (1) or (4), provides the suitable minimum extent of bed activity.

d. Mean Bed Slope. A sloping bed can affect the process of motion initiation through the component of grain weight along the bed. Available studies support the accuracy of the present criterion for sand motion initiation on plane slopes gentler than 1 on 15. On a steeper sand slope, available data indicate a lower velocity than that given by the present criterion is required for sand motion, so that the present procedure would provide the minimum extent of bed activity.

A sloping bed causes wave transformation that is more complicated than the wavelength change included in the present procedure. Available information supports linear theory results for a wave height change in shoaling on slopes of 1 on 20 or gentler if

$$\frac{gHT^2}{d^2} \leq 30 \tag{9}$$

It is certainly consistent with the accuracy of the fundamental correlations in equations (1) and (2) to ignore the usually small wave height changes given by linear theory whenever

$$\frac{d}{L} > 0.075 \tag{10}$$

The present procedure presumes that the stated requirements of equations (9) and (10) and of a gentle slope are satisfied.

e. Wave Spectrum. There is no simple alternative to the customary engineering assumption that an irregular surface wave field may be represented by a single wave height and period. However, there is no direct evidence that the significant wave condition is an adequate representation in considering sand motion initiation by waves having a spectrum of height, frequency, or direction.

f. Superimposed Steady Flow. Some evidence indicates that the present criterion for sand motion remains appropriate with a small current superimposed on an oscillatory flow, provided that the current speed is less than $(0.1\xi\omega)$. Hammond and Collins (1979) provide the first data on sand motion initiation with steady and oscillatory flows in the same direction. These results indicate that the threshold peak velocity in combinations of waves and currents is fairly close to that with waves alone. Thus, in a situation with a known steady flow, this velocity can be subtracted from the calculated threshold peak near-bottom fluid velocity and then the wave conditions required for sand motion can be determined by the procedure in Section II,2.

An alternative is to ignore the steady-flow velocity, and regard calculated results as indicating the minimum extent of bed activity due to waves. In situations with significant astronomical tides, water depth should be considered as being with respect to mean low water (MLW) datum.

III. EXAMPLE CALCULATIONS OF CRITICAL CONDITIONS

The following example problems demonstrate the use of the present procedure in calculating critical conditions for sand motion initiation by waves.

* * * * * * * * * * * * * * * EXAMPLE PROBLEM 1 * * * * * * * * * * * * * * *

GIVEN: At Point Mugu, California (34°07' N., 119°09' W.), the average yearly wave period is 11 seconds, according to records from a near-bottom pressure wave gage in a 31-foot (9.4 meters) mean water depth (Thompson, 1977). Also, γ' is 1.59 (quartz sand in saltwater), ν is 1.28×10^{-5} square feet (0.0119 square centimeter) per second (15° Celsius mean water temperature; National Ocean Survey, 1970), and the typical offshore sediment median diameter D is 0.00033 foot (0.01 centimeter).

FIND: The minimum wave height required for sand motion in a water depth of 60 feet (18.3 meters) with a wave of the average frequency ($\omega = 2\pi/11.0 = 0.571$ radian per second) for this site.

SOLUTION: Equation (2) gives

$$(\xi\omega)_m = (8\ \gamma' g\ D)^{0.5} = [8(1.59)(32.2)(0.00033)]^{0.5} = 0.37 \text{ ft } (11.17 \text{ cm})/\text{s}$$

and equation (3) gives

$$\varepsilon = \frac{(\xi\omega)_m\ D^{0.29}}{266.5\ \omega^{0.355}\ \nu^{0.645}} = \frac{(0.37)(0.00033)^{0.29}}{266.5\ (0.571)^{0.355}\ (1.28 \times 10^{-5})^{0.645}} = 0.24$$

indicating that the near-bed boundary layer would not be thoroughly mixed by the effect of grain roughness on an incident laminar flow, so equation (4) may also be considered. Equation (1) gives

$$(\xi\omega)_v = \frac{0.35\ D^{0.25}(\gamma' g)^{0.75}}{\omega^{0.5}} = \frac{0.35(0.00033)^{0.25}[(1.59)(32.2)]^{0.75}}{(0.571)^{0.5}} = 1.19\ \text{ft}$$

(36.35 cm)/s

and equation (5) gives

$$\delta = 2 - \frac{(\xi\omega)_v}{1.15} = 0.96$$

then equation (4) becomes

$$(\xi\omega)_t = \frac{\varepsilon^2(\xi\omega)_m + \delta^2(\xi\omega)_v}{\varepsilon^2 + \delta^2} = \frac{(0.24)^2(0.37) + (0.96)^2(1.19)}{(0.24)^2 + (0.96)^2} = 1.14\ \text{ft}$$

(34.94 cm)/s

For the specified situation, d = 60 ft and g = 32.2 ft (9.81 m)/s^2, so

$$\frac{\omega^2\ d}{g} = \frac{(0.571)^2 \times 60}{32.2} = 0.61$$

and, taking this as the value of [x(tanh x)] according to equation (7), the Figure gives the abscissa

$$x = \frac{2\pi d}{L} = 0.87$$

Also from the Figure,

$$\sinh(0.87) = 0.98$$

Using the value of $(\xi\omega)_m$, the minimum wave height for sand motion is

$$\left(H_{min}\right)_m = \frac{2(\xi\omega)_m \sinh\left(\frac{2\pi d}{L}\right)}{\omega} = \frac{2(0.37)(0.98)}{0.571} = 1.27\ \text{ft}\ (0.39\ \text{m})$$

while using the value of $(\xi\omega)_t$, the minimum wave height for sand motion would be

$$\left(H_{min}\right)_t = \frac{2(\xi\omega)_t \sinh\left(\frac{2\pi d}{L}\right)}{\omega} = \frac{2(1.14)(0.98)}{0.571} = 3.9\ \text{ft}\ (1.19\ \text{m})$$

DISCUSSION: According to wave data reported by Thompson (1977), $(H_{min})_m$ is on the order of one-half the average significant height for Point Mugu, while $(H_{min})_t$ is considerably larger than the average significant wave height. As stated, available evidence generally supports the use of $(\xi\omega)_m$ in field situations, and additional information for this site further indicates $(H_{min})_m$ is the appropriate calculated critical condition.

Mugu Canyon extends close to the coastline, with a water depth at its head of about 50 feet (15 meters). Shepard and Dill (1966) state that Mugu Canyon head presently receives a good supply of sediments, supporting the value of $(H_{min})_m$ in that usual waves can thus agitate nearshore sands in the water depths near this canyon head. Measurements of wave effects on the sea bottom off southern California by Inman (1957) and Vernon (1965) confirm that waves appreciably lower than $(H_{min})_t$ cause sand movement in water depths on the order of 60 feet at comparable sites.

With

$$H = 1.27 \text{ ft } (0.39 \text{ m}) \text{ and } (2\pi d/L) = 0.98,\ (d/L) = 0.16 > 0.075,$$

$$\frac{gHT^2}{d^2} = \frac{(32.2)(1.27)(11)^2}{(60)^2} = 1.37 < 30, \text{ and}$$

$$S = \frac{HL^2}{2d^3} = \frac{H}{2d\left(\frac{d}{L}\right)^2} = \frac{1.27}{(2)(60)(0.16)^2} = 0.41 < 8,$$

so that equations (8), (9), and (10) are satisfied. However, the expected bed forms in 60-foot water depths and the appreciable tidal range at this site indicate that 11-second waves somewhat lower than 1.27 feet in height might induce sand motion.

* * * * * * * * * * * * * * * EXAMPLE PROBLEM 2 * * * * * * * * * * * * * * *

GIVEN: A laboratory movable-bed test is to be performed with sediment of median diameter D = 0.00066 foot (0.020 centimeter), wave height H = 0.5 foot (15 centimeters), and wave period T = 2 seconds. Also, $\gamma' = 1.66$ (quartz sand in freshwater) and $\nu = 1.08 \times 10^{-5}$ square foot per second (0.010 square centimeter per second)(20° Celsius average water temperature).

FIND: Maximum water depth for sand motion in the given situation.

SOLUTION: Equation (1) gives

$$(\xi\omega)_v = \frac{0.35\ D^{0.25}(\gamma' g)^{0.75}}{\omega^{0.5}} = \frac{0.35(0.00066)^{0.25}[(1.66)(32.2)]^{0.75}}{(\pi)^{0.5}} = 0.63 \text{ ft}$$

(19.04 cm)/s

With

$$[\omega\ H/2(\xi\omega)_v] = [(\pi)(0.5)/2(0.63)] = 1.25$$

Figure shows

$$\sinh^{-1}(1.25) = 1.05 = (2\pi d/L) \text{ and } [1.05 \tanh(1.05)] = 0.82$$

Equation (7) shows

$$\left(d_{max}\right)_v = \frac{g\left[\frac{2\pi d}{L} \tanh\left(\frac{2\pi d}{L}\right)\right]}{\omega^2} = \frac{(32.2)(0.82)}{\pi^2} = 2.7 \text{ ft } (80.5 \text{ cm}) \text{ as the}$$

maximum water depth for sand motion initiation.

DISCUSSION: Since $(d/L) = (1.05/2\pi) = 0.17$, $S = (H/2d)(L^2/d^2) = [(0.5)/2(2.7)] (1/0.17)^2 = 3.2$ and $(gHT^2/d^2) = [(32.2)(0.5)(2)^2/(2.7)^2] = 8.8$, all the limitations on equation (1) as well as equations (8), (9), and (10) are satisfied. A mean water depth less than 3 feet (0.91 meter), with a gentle offshore sand slope and the given wave conditions, should be adequate to include the entire wave-agitated bed.

If artificial roughness is installed to provide a thoroughly mixed bottom boundary layer in the incident wave, note that equation (2) gives

$$(\xi\omega)_m = (8\ \gamma' g\ D)^{0.5} = [8(1.66)(32.2)(0.00066)]^{0.5} = 0.53 \text{ ft}$$

(16.14 cm)/s

and that equations (6) and (7) then give

$$\left(d_{max}\right)_m = 3.2 \text{ ft } (95.8 \text{ cm})$$

so that a larger mean water depth would be required. Note also that

$$\varepsilon = \frac{(\xi\omega)_m\ D^{0.29}}{266.5\ \omega^{0.355}\ \nu^{0.645}} = \frac{(0.53)(0.00066)^{0.29}}{266.5(\pi)^{0.355}\ (1.08 \times 10^{-5})^{0.645}} = 0.25$$

so that roughness additional to that of a plane sand slope would definitely be required to make the field criterion in equation (2) applicable.

IV. SUMMARY

This report presents a procedure for calculating peak oscillatory velocity causing sand motion, and for converting this velocity into critical wave conditions. Having specified the material characteristics (γ', g, D, and ν) and the wave characteristics (T and either d or H), the procedure provides the remaining parameter--either the minimum wave height for sand motion in a given water depth, or the maximum water depth for sand motion with a given wave height. This permits estimating the seaward extent of bed activity in laboratory and field situations. Considering the assumptions and the factors ignored in developing this procedure, in certain situations the present calculations must be regarded as a minimum estimate of the extent of bed activity for the specific wave condition.

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