FIGURE 2

MAXIMUM BOTTOM VELOCITY OF WATER PARTICLES AS A FUNCTION OF PERIOD AT $d = \frac{400}{GT^2}$
Wave Generated Oscillatory Currents Along the Bottom in the Eulittoral and Sublittoral Zones

(With graphs for determining maximum horizontal velocity, maximum displacement, and mean acceleration.)

Lee M. Hunt
May 1961

Mine Advisory Committee

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NATIONAL ACADEMY OF SCIENCES
NATIONAL RESEARCH COUNCIL
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LIST OF SYMBOLS

A = wave amplitude = $\frac{H}{2}$
a = mean particle acceleration
C = shallow water phase or wave velocity
$C_0$ = deep water phase or wave velocity
D = diameter of particle orbit
d = depth of water, measured from still water level to the bottom; taken as positive downward
e = base of Naperian logarithms = 2.718
g = acceleration of gravity - 32.2 ft/sec$^2$
H = shallow water wave height
$H_0$ = deep water wave height
k = wave number = $\frac{2\pi}{L}$
L = shallow water wave length
$L_0$ = deep water wave length
n = ratio of group velocity to phase velocity
T = wave period
t = time
$U_d$ = deep water horizontal particle velocity
$U_i$ = intermediate water horizontal particle velocity
$U_s$ = shallow water horizontal particle velocity
<table>
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<tr>
<td>$U_{\text{max}}$</td>
<td>maximum horizontal particle velocity</td>
</tr>
<tr>
<td>$W_d$</td>
<td>deep water vertical particle velocity</td>
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<td>$W_i$</td>
<td>intermediate water vertical particle velocity</td>
</tr>
<tr>
<td>$W_s$</td>
<td>shallow water vertical particle velocity</td>
</tr>
<tr>
<td>$x$</td>
<td>horizontal coordinate (arbitrary origin), positive in direction of wave advance</td>
</tr>
<tr>
<td>$z$</td>
<td>depth below still-water level; taken as negative downward</td>
</tr>
<tr>
<td>$\xi_d$</td>
<td>deep water horizontal displacement of particle from its mean position</td>
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<tr>
<td>$\xi_i$</td>
<td>intermediate water horizontal displacement of particle from its mean position</td>
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<tr>
<td>$\xi_s$</td>
<td>shallow water horizontal displacement of particle from its mean position</td>
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<tr>
<td>$\xi_{\text{max}}$</td>
<td>maximum horizontal displacement of particle from its mean position</td>
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<td>$\sigma$</td>
<td>angular frequency $= \frac{2\pi}{T}$</td>
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INTRODUCTION

Wave generated oscillatory currents along the ocean floor provide one of the more important forces participating in the erosion, transportation, and deposition of marine sediments. These currents are especially active in the eulittoral zone which ranges from the high tide level to a depth of 150 feet. Significant currents in the sublittoral zone, which continues from the lower border of the eulittoral zone to a depth of 600 feet or the edge of the continental shelf, are generated only by exceptionally long period waves. The effect of these currents has long been of importance to marine geologists and coastal engineers, and their importance can only be enhanced by the increasing amount of instruments and installations being placed on the ocean bottom in these zones.

Due to turbulence as well as the oscillatory nature of wave generated bottom currents, attempts to measure their magnitudes have met with considerable difficulty. Since observations made in controlled laboratory tests and in some field tests show reasonable agreement between actual and theoretical particle motion\(^1,2,3,4\) these currents are usually calculated from theory. This report discusses briefly the theory upon which these calculations are based and then, in order to facilitate the use of the theory, provides graphs of maximum particle velocity, maximum particle displacement, and mean particle acceleration at the bottom as a function of depth, wave period, and wave height. The curves are drawn such that if the latter three variables are known the former three can be read directly from the graphs. If maximum particle velocity and displacement over the entire water column is required the reader is referred to GRAPHS FOR OBTAINING ORBITAL DISPLACEMENTS AND VELOCITIES, Scripps Institution of Oceanography, Wave Project No. 71, Nov. 12, 1947.

In using the graphs it should be kept in mind that the theory does not take into consideration the spectral nature of some naturally occurring waves in shallow water. The values presented then, represent a somewhat simplified picture of current characteristics under these conditions. It might be pointed out, however, that due to the filtering out of waves with periods smaller than the one considered, bottom currents calculated from theory are more accurate than those higher in the water column.
CHARACTERISTICS OF ORDINARY GRAVITY WAVES
TRANSITING FROM "DEEP" TO "SHALLOW" WATER

Ordinary Gravity Waves

Waves having periods ranging from 1 to 30 seconds are known as ordinary gravity waves as distinguished from ultra-gravity waves with a period range of 0.1 to 1 second, and infra-gravity waves whose period range is 30 seconds to 5 minutes. Ordinary gravity waves include the wind generated waves known as seas while under the direct influence of the wind, and swell after they have begun to decay in a region of lighter wind or calm. Seas generally have a shorter period than swell with the division being at around 9 seconds. There is, however, some overlap. This whole band of ordinary gravity waves contains a large fraction of the total wave energy and is, therefore, important to a variety of problems.

Ordinary gravity waves are generated by the pressure and tangential stresses applied to the water surface by wind action. Dimensional characteristics, therefore, depend upon wind velocity, duration, and fetch as well as the distance the waves have traveled from their area of generation. This last point is due to the decay undergone by waves once the generating force is removed. Decay may be a slow process as shown by the summer swell which breaks on the California coast after traveling more than 4000 miles from their generation area in the "Roaring Forties" and "Furious Fifties" of the South Pacific.

Transition from "Deep" to "Shallow" Water Waves

Ordinary gravity waves may be divided into deep (short) and shallow (long) water waves through a consideration of the relationship between phase velocity, wave length, and water depth. The phase velocity can be evaluated with sufficient accuracy from the classical equation for gravity waves of small steepness (1,2,5):

\[ C^2 = \frac{gL}{2\pi} \tanh kd. \]  \hspace{1cm} (1)
If the relative depth \((d/L)\) is greater than 0.5, then the hyperbolic tangent can be replaced by unity to an accuracy of one per cent. Equation (1) is thereby reduced to

\[
C^2 = \frac{gL}{2\pi}.
\]  

(2)

Waves under conditions where \(d/L\) is greater than 0.5 and where the phase velocity is independent of depth are called deep water waves, the wavelength of which is given by

\[
L_0 = \frac{g}{2\pi} T^2.
\]  

(3)

If, on the other hand, \(d/L\) is less than 0.05, the hyperbolic tangent can be replaced by the argument \(2\pi d/L\) to the same accuracy and equation (1) becomes

\[
C^2 = gd.
\]  

(4)

Waves under these conditions are independent of wave length, but dependent upon depth, and are called shallow water waves.

Waves whose relative depth lies between 0.05 and 0.5 are termed intermediate and equation (1) must be used.

Throughout the remainder of this paper, unless otherwise specified, shallow water will be used to indicate any relative depth less than the depth at the deep to shallow water wave transition point as given by

\[
d = \frac{1}{4\pi} gT^2
\]  

(5)

or \(1/2 L_0\).

**Orbital Motion of Water Particles**

Associated with the motion of waves is a motion of the water particles themselves. In the deep water case this motion is in the form of circles in
the vertical plane with the water particles moving in the direction of wave propagation under the wave crest and in the opposite direction under the trough. The time required for one complete orbit is equal to the period of the wave. The orbital diameter is given by

\[ D = H e^{kz}, \]

(6)

hence \( D \) decreases exponentially with increasing depth. The following rule is often useful: The orbital diameter, (equal to the wave height at the surface), is reduced by one-half with each depth increase equal to one-ninth of the wave length.

As an example a deep water wave having dimensions \( T = 10 \) seconds, \( L_0 = 512 \) feet, and \( H = 22 \) feet will have a surface orbit of 22 feet in diameter. At a depth equal to one-half the wave length (256 feet) the orbital diameter is 0.95 feet, and at a depth equal to the wave length (512 feet) the orbital diameter is 0.042 feet. Since the orbital diameter at \( 1/2 L_0 \) is only \( 1/23 \) that of the surface orbit it can be seen that the bottom can have no significant effect on the character of the waves as long as \( d \) exceeds \( 1/2 L_0 \).

As any wave crosses its particular transition point from deep to shallow water, an increasing potential orbital diameter is brought in contact with the bottom. However, at the sea bed, the component of motion normal to the bottom must vanish, and the response of the water particles over the entire water column to this transition is a tendency toward elliptical rather than circular orbits. Moreover, the eccentricity of the elliptical orbits increases with decreasing depth.

Particle Velocity, Displacement, and Acceleration

The speed with which water particles move around their orbits — essentially uniform while they are circular — is no longer so after they are transformed into ellipses, but is greatest near the crest and trough of the wave. This discrepancy between the speeds along different parts of the elliptical orbit increases with decreasing depth, since it is proportional to the length of the major axis of the ellipse. Since the transformation of the orbit from circle to ellipse consists of an expansion of the horizontal axis, with the vertical axis changing only as much as the height of the waves, the speed with which the water particle advances in the crest and recedes in the trough grows greater as the depth decreases.
Figures 1 and 2 graphically illustrate the relative depth of transition as a function of period, the depth range over which the maximum bottom particle velocity at the transition point is exceeded, and the relationship between maximum particle velocity at the transition point and wave period.

Horizontal and vertical particle velocity for deep, intermediate, and shallow water are given by

\[ U_d = A \sigma^{kz} \cos(kx - \sigma t) \quad (7) \]

\[ W_d = A \sigma^{kz} \sin(kx - \sigma t) \quad (8) \]

\[ U_i = A \sigma \frac{\cosh k (z + d)}{\sinh kd} \cos(kx - \sigma t) \quad (9) \]

\[ W_i = A \sigma \frac{\sinh k (z + d)}{\sinh kd} \sin(kx - \sigma t) \quad (10) \]

\[ U_s = \frac{A \sigma}{kd} \cos(kx - \sigma t) \quad (11) \]

\[ W_s = A \sigma (1 + \frac{z}{d}) \sin(kx - \sigma t) \quad (12) \]

respectively. The above equations apply for a water level profile which varies as \( A \cos(kx - \sigma t) \). At the bottom, of course, \( -z \) is equal to \( d \), and \( W \) becomes 0. If only the maximum velocity at the bottom is considered \((x, t = 0)\) equations (9) and (11) may be rewritten as

\[ U_{\text{max}} = A \sigma \frac{1}{\sinh kd} \quad (13) \]

\[ U_{s\text{max}} = \frac{A \sigma}{kd} = A \sqrt{\frac{g}{d}} \quad (14) \]

Particle displacement is taken as the displacement in one direction of a particle from its mean position. Twice the maximum displacement then is the total range of particle excursion. The horizontal and vertical displacement is given by

\[ \xi_d = A e^{kz} \cos(kx - \sigma t) \quad (15) \]
FIGURE 1

BARS REPRESENT DEPTH OF TRANSITION FROM SHORT TO LONG WAVES

\[ d = \frac{1}{4\pi} g T^2 1/2 L_0 \]

AND THE DEPTH RANGE OVER WHICH THE STATED MAXIMUM BOTTOM VELOCITY OF WATER PARTICLES PER FOOT OF WAVE HEIGHT ARE EXCEEDED.
FIGURE 2
MAXIMUM BOTTOM VELOCITY OF WATER PARTICLES AS A FUNCTION OF PERIOD AT $d = \frac{1}{4\pi} GT^2$
\[\xi_d = A e^{kz} \sin (kx - \sigma t)\]  
(16)

\[\xi_i = A \frac{\cosh k(z + d)}{\sinh kd} \cos (kx - \sigma t)\]  
(17)

\[\xi_i = A \frac{\sinh k(z + d)}{\sinh kd} \sin (kx - \sigma t)\]  
(18)

\[\xi_s = \frac{A}{kd} \cos (kx - \sigma t)\]  
(19)

\[\xi_s = A \left(1 + \frac{z}{d}\right) \sin (kx - \sigma t)\]  
(20)

As in the case of particle velocity, particle displacement has no vertical component at the bottom and if maximum displacement is considered equations (17) and (19) can be rewritten as

\[\xi_{imax} = A \frac{1}{\sinh kd}\]  
(21)

\[\xi_{smax} = \frac{A}{kd} = 2\pi T A \sqrt{\frac{g}{d}}\]  
(22)

At the bottom where the particle motion is back and forth with no vertical component a particle moves from \(U = 0\) to \(U_{\text{max}}\) to \(U = 0\) in any one direction and the mean acceleration over one-quarter cycle may be computed by a consideration of one-fourth of the total particle excursion. The mean acceleration of a particle at the bottom, then, is given by

\[a = \frac{4 U_{\text{max}}}{T}\]  
(23)

**Effect of Shallow Water on Wave Form**

Wave period undergoes no significant change under shoaling conditions and requires no subscript to designate deep or shallow water. At \(\approx \frac{1}{2} L_0\), however, \(H, L, \text{ and } C\) begin to undergo changes as shown in Figure 3. As can be seen the shallow water wave length as given by

\[L = L_0 \tanh kd\]  
(24)
and phase velocity as given by equations (1) and (4) are related such that they decrease at the same rate. Under these conditions, and with the period being constant, the shallow water wave height as given by

$$ H = H_0 \sqrt{\frac{c_0}{zn}} $$

(25)

must undergo change. As shown in Figure 3 wave height undergoes a reduction beginning at \( d/L_0 \approx 0.5 \), reduces to about \( 0.914 H_0 \) at \( d/L_0 = 0.615 \), regains its deep water value at about \( d/L_0 = 0.06 \), and exceeds \( H_0 \) past this relative depth. Figure 4 illustrates the effect of this variability of wave height under shoaling conditions on maximum particle velocity at the bottom by plotting it against \( H_0 \) held constant. This graph represents waves undergoing no refraction. It should also be noted that equation (25), based on linear wave theory, holds only for waves of sufficiently small steepness and does not hold in the vicinity of the breaker zone. The solitary wave theory, in this zone, gives a better approximation. (6)

EXPLANATION OF FIGURES AND TABLES

**Figure 5**

Maximum particle velocities per foot of wave height for wave periods from two to twenty seconds have been plotted against depth in Figure 5. Since there is no close relationship between a wave's height and its length and period, equation (13) has been rewritten as

$$ \frac{U_{max}}{H} = \frac{\pi}{T \sinh kd} $$

(26)

and the actual particle velocity is obtained by multiplying the velocity value as read from the abscissa by the desired wave height.

To provide a greater continuity and accuracy the formula for intermediate relative depth has been used in both figure 5 and Figure 6.
Figure 4: Showing maximum bottom velocity of water particles as a function of depth (H). (1) H held equal to H; (2) H varying under normal shoaling conditions. H = 10 feet, U_{max} (feet per second)

Depth (feet)
Figure 6

Maximum particle displacement per foot of wave height for periods from two to twenty seconds have been plotted against depth in Figure 6. As in the case of particle velocity equation (21) has been rewritten as

\[ \frac{\xi_{\text{max}}}{H} = \frac{1}{2 \sinh kd} \]  

(27)

and maximum particle displacement is obtained by multiplying the abscissa value by the desired wave height.

Figure 7

In considering the effect of bottom particle velocity on sediments it is often desirable to know the velocity distribution over the path of particle excursion. The time range, for instance, over which a particle has exceeded a particular velocity is often useful. In order to facilitate the calculation of a velocity curve for a desired height, period, and depth the mean acceleration per foot of wave height for periods from two to twenty seconds have been plotted against depth in Figure 7. As in Figures 5 and 6 the abscissa value is multiplied by the desired wave height.

Table 1

The particle velocity, displacement, and acceleration values used in plotting the various curves for each depth and period used are listed in Table I.
TABLE I
Values for Maximum Velocity, Displacement, and Acceleration of Bottom Particle per Foot of Wave Height as a Function of Depth and Period

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<tr>
<th>T</th>
<th>(d)</th>
<th>$U_{max}/H$</th>
<th>$\xi_{max}/H$</th>
<th>$a/H$</th>
<th>T</th>
<th>(d)</th>
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| 240   | 0.033       | 0.052         | 0.013 | 220   | 0.041       | 0.066         | 0.016 |
| 200   | 0.053       | 0.084         | 0.021 | 180   | 0.066       | 0.106         | 0.026 |
| 160   | 0.084       | 0.133         | 0.034 | 140   | 0.105       | 0.168         | 0.042 |
| 120   | 0.132       | 0.211         | 0.053 | 100   | 0.167       | 0.266         | 0.067 |
| 90    | 0.188       | --            | --    | 90    | 0.188       | --            | --    |
| 80    | 0.212       | 0.338         | 0.085 | 70    | 0.240       | --            | --    |
| 60    | 0.275       | 0.438         | 0.110 | 60    | 0.318       | --            | --    |
| 50    | 0.374       | 0.596         | 0.150 | 50    | 0.454       | --            | --    |
| 40    | 0.582       | 0.927         | 0.233 | 40    | 0.222       | 0.039         | 0.008 |
| 30    | 0.027       | 0.047         | 0.010 | 30    | 0.049       | 0.085         | 0.018 |
| 20    | 0.033       | 0.058         | 0.012 | 20    | 0.040       | 0.070         | 0.015 |
|       | 0.022       | 0.039         | 0.008 | 11    | 0.022       | 0.039         | 0.008 |
|       | 0.027       | 0.047         | 0.010 | 10    | 0.027       | 0.047         | 0.010 |
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|       | 0.049       | 0.085         | 0.018 | 7     | 0.049       | 0.085         | 0.018 |
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|       | 0.066       | 0.106         | 0.018 | 5     | 0.066       | 0.106         | 0.018 |
|       | 0.079       | 0.129         | 0.018 | 4     | 0.079       | 0.129         | 0.018 |
|       | 0.092       | 0.152         | 0.018 | 3     | 0.092       | 0.152         | 0.018 |
|       | 0.105       | 0.175         | 0.018 | 2     | 0.105       | 0.175         | 0.018 |
|       | 0.118       | 0.198         | 0.018 | 1     | 0.118       | 0.198         | 0.018 |
|       |             |               |       |       | 320   | 0.022       | 0.039         | 0.008 |
|       |             |               |       |       | 300   | 0.027       | 0.047         | 0.010 |
|       |             |               |       |       | 280   | 0.033       | 0.058         | 0.012 |
|       |             |               |       |       | 260   | 0.040       | 0.070         | 0.015 |
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