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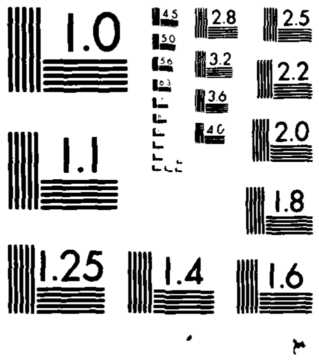

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Seaward Limit of Significant Sand Transport by Waves: An Annual Zonation for Seasonal Profiles

by

Robert J. Hallermeier

COASTAL ENGINEERING TECHNICAL AID NO. 81-2

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Sand characteristics and annual wave statistics at a site are used to determine two water depths bounding a shoal zone on the beach profile. This zonation is based on two thresholds of wave-induced sand agitation, so that expected waves during a year have neither strong nor negligible effects on the sand bottom within the shoal zone. The calculation procedure and representative results for the shoal zone bounds are presented to supplement techniques for estimating a seaward limit of significant sand transport given in the Shore Protection Manual (SPM). A calculator program is provided.

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PREFACE

This report provides a new technique for seaward-limit estimation, supplementing those given in Section 4.523 of the Shore Protection Manual (SPM). Two calculated water depths locate the edges of a buffer region called the shoal zone, which is defined so that significant alongshore transport and intense onshore-offshore transport by waves occur landward of this zone, and only insignificant onshore-offshore transport by waves occurs seaward of this zone. This profile zonation and guidance on its applications are interim results from an ongoing study conducted within the beach behavior and restoration research program of the U.S. Army Coastal Engineering Research Center (CERC).

The report was written by Dr. Robert J. Hallermeier, Oceanographer, under the general supervision of C. Mason, Chief, Coastal Processes Branch, and then Dr. R.M. Sorensen, Chief, Coastal Processes and Structures Branch.

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.

Bishop

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

A

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FIGURES

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 (angel)	0.01745	radians
Fahrenheit degrees	5/9	Celsius degrees or Kelvins

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	water depth
d_i	water depth at seaward bound of shoal zone
d_ℓ	water depth at landward bound of shoal zone
g	acceleration of gravity
H	wave height
$\bar{H}_s$	annual mean significant wave height
$H_{s0.137}$	extreme significant wave height exceeded 12 hours per year
H_{s50}	annual median significant wave height
L	linear wavelength
L_o	linear wavelength in deep water
T	wave period
$\bar{T}_s$	annual mean significant wave period
$u_{max}(-d)$	maximum linear wave-induced horizontal velocity near the bed
x	argument of hyperbolic functions in Figure 4
γ'	ratio of density difference between sand and fluid to fluid density
σ	annual standard deviation of significant wave height

SEAWARD LIMIT OF SIGNIFICANT SAND TRANSPORT BY WAVES: AN ANNUAL ZONATION FOR SEASONAL PROFILES

by
Robert J. Hallermeier

I. INTRODUCTION

Certain coastal activities require consideration of the seaward limit to significant wave-induced bed activity along a sand beach profile. Examples include design of nearshore structures, subaqueous beach fill, and borrow or disposal of material. The seaward limit to significant sand movement by waves clearly depends on both wave and sand characteristics through the mechanisms of wave agitation of sand. However, available guidelines on the seaward limit (U.S. Army, Corps of Engineers, Coastal Engineering Research Center, 1977, pp. 4-63 to 4-70) proceed from indirect or qualitative consideration of wave-sand interactions. This report provides a new quantitative procedure for seaward-limit estimation based on definite wave-sand interactions. A comprehensive discussion of the present procedure and of other seaward-limit treatments is provided in Hallermeier (1981).

The present procedure defines an annual beach profile zonation related to the seaward limit. Figure 1 is a schematic illustration of this zonation and identifies the terminology used here. The water depths d_ℓ and d_i, respectively the landward and seaward bounds of the shoal zone, are calculated in Section II, using sand characteristics and statistics of annual wave climate for a given locality. This shoal zone is a buffer area where expected waves have neither strong nor negligible effects on the sand bed during a typical annual cycle of wave action, according to available knowledge of sand movement by waves.

The water depth, d_ℓ, gives a seaward limit to extreme surf-related effects, so that significant alongshore transport and intense onshore-offshore transport are restricted to water depths less than d_ℓ. The water depth, d_i, gives a seaward limit to sand motion by usual waves, so that significant onshore-offshore transport is restricted to water depths less than d_i. The seaward limit in sandy regions reasonably falls within this calculated shoal zone, although placement of the limit depends on the particular engineering application, as pointed out in Section III.

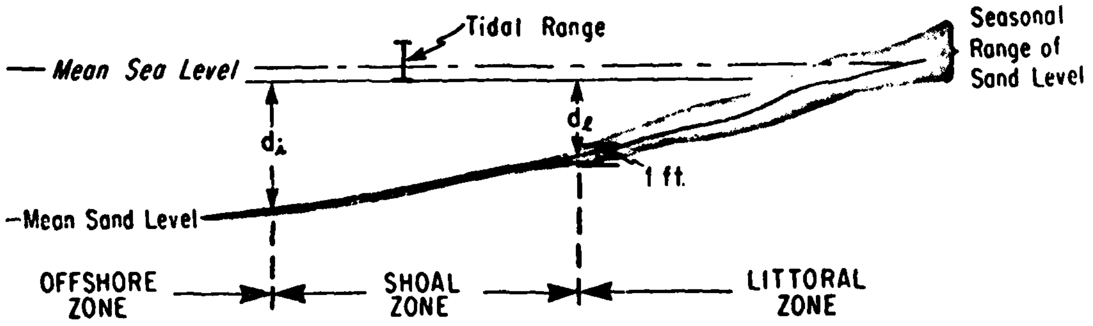

Figure 1. Definition sketch of annual sand beach zonation and terminology.

Since the shoal zone has a definite physical basis, the present calculation procedure may reduce the need for detailed site-specific investigations of physical processes, and certainly aids in designing such investigations at localities where wave climate is known. Nearshore measurements of wave climate along U.S. coasts provide a basis for the example calculations given in Section IV. The calculated shoal zone extent is to be considered in conjunction with other information pertinent to the seaward limit of the wave-dominated sand profile.

II. BASIC EQUATIONS AND SOLUTION TECHNIQUES

The water depths d_ℓ and d_i are calculated from relationships giving the threshold flow energy for two distinct wave interactions with a sand bed. The major assumptions involved are the accuracy of linear wave theory for calculations of near-bottom maximum flow velocity, and a modified exponential distribution of nearshore wave heights.

The landward bound to the shoal is determined from the relationship

$$\frac{u^2_{max(-d)}}{\gamma' g d} = 0.03 \qquad (1)$$

where

$u_{max(-d)}$ = the maximum wave-induced horizontal fluid velocity near the bed

γ' = the ratio of the density difference between sand and fluid to the fluid density

g = the acceleration due to gravity

d = the mean water depth.

Equation (1) describes a definite threshold of erosive sand-bed agitation by steady wave action, and $u_{max(-d)}$ will be taken as that due to an extreme wave height exceeded 12 hours per year in determining d_ℓ. The water depth then defined by equation (1) agrees with field data on the maximum water depth for significant profile changes (elevation excursions greater than ±0.5 foot or ±0.15 meter) throughout a yearly cycle of wave climate.

Linear wave theory gives

$$u_{max(-d)} = \frac{\pi H}{T\,\{\sinh\,(2\pi d/L)\}} \qquad (2)$$

where H is the wave height, T the wave period, L the local wavelength at d; and

$$\left\{\frac{L}{\tanh(2\pi d/L)}\right\} = L_o = \left(\frac{gT^2}{2\pi}\right) \qquad (3)$$

where L_o is wavelength in deep water.

The modified exponential distribution approximating typical measured nearshore wave heights is shown in Figure 2. In terms of standard annual wave

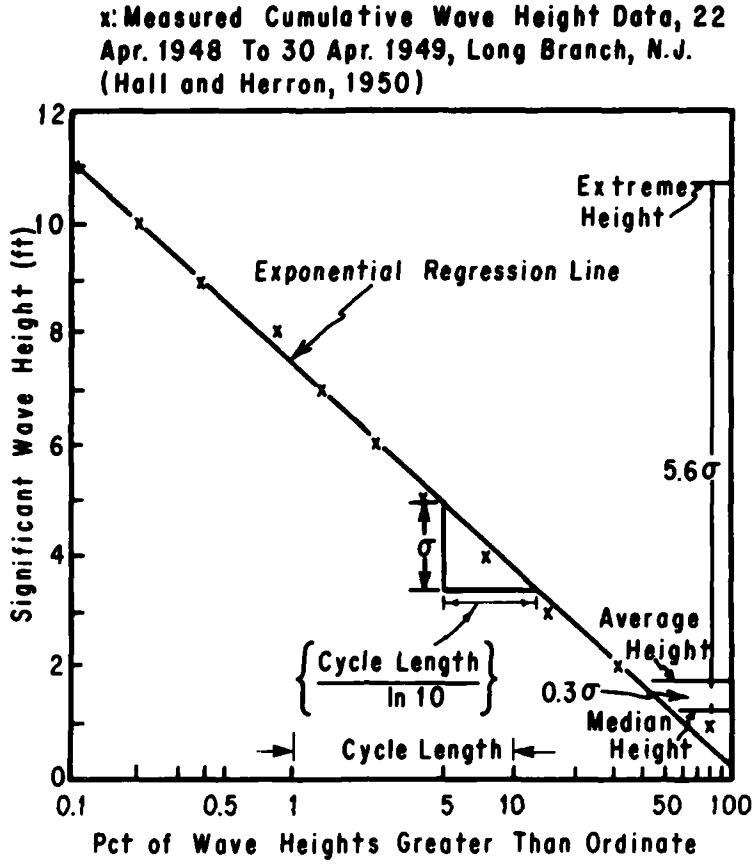

Figure 2. Graphical definition of statistics of exponential cumulative wave height distribution.

statistics, the extreme significant wave height exceeded 12 hours per year (0.137 percent) is

$$H_{s0.137} = \bar{H}_s + 5.6\ \sigma \tag{4}$$

where $\bar{H}_s$ is annual average significant wave height, and σ is the annual standard deviation of significant wave height. For simplicity, the period associated with this extreme wave condition is taken to be the average significant wave period $\bar{T}_s$, with fair justification. The wave statistics $\bar{H}_s$, σ, and $\bar{T}_s$ should be defined by one or more full years of daily or more frequent measurements.

Using equations (2), (3), and (4), equation (1) can be rewritten as

$$\left\{\frac{2\pi d_\ell}{L}\right\} \sinh^2 \left\{\frac{2\pi d_\ell}{L}\right\} \tanh\left\{\frac{2\pi d_\ell}{L}\right\} = \frac{\pi^2(\bar{H}_s + 5.6\ \sigma)^2}{0.03\gamma'(g\bar{T}_s^2/2\pi)^2} \tag{5}$$

and the values of γ', $\bar{H}_s$, σ, and $\bar{T}_s$ determine a single value of $(2\pi d_\ell/L)$. The value of d_ℓ can be accurately determined using the iterative root-finding calculator program presented in the Appendix. Alternatively, for $\gamma' = 1.6$ (quartz sand in saltwater), Figure 3 provides a graphical solution of equation (5). The dimensionless value of $(2\pi d_\ell/L)$ is converted to d_ℓ by multiplying by $\{(L_o/2\pi)\tanh(2\pi d_\ell/L)\}$ (see eq. 3); Figure 4 provides the needed graph of (tanh x) versus x. Another alternative for $\gamma' = 1.6$ is the first-order analytical approximation,

$$\tilde{d}_\ell = 2\bar{H}_s + 11\,\sigma, \tag{6}$$

which is convenient and usually within ±5 percent of an exact calculation.

The seaward bound to the shoal zone is determined from the relationship

$$\frac{u^2_{max}(-d)}{\gamma' g D} = 8, \tag{7}$$

where D is the median sand diameter characteristic of the shoal zone bed, e.g., at mean water depth of $(1.5\ d_\ell)$. Equation (7) gives the threshold of sand motion by wave action in field conditions, and $u_{max}(-d)$ will be taken as that due to the median (50 percent) wave condition. For this wave condition, equation (7) along with the depth dependence in equation (2) defines a maximum water depth for sand motion, d_i, which corresponds to the seaward limit of the usual wave-constructed profile.

The modified exponential distribution gives the median significant wave height as

$$H_{s50} = \bar{H}_s - 0.3\,\sigma \tag{8}$$

The period associated with this median wave height is also taken to be the average wave period $\bar{T}_s$. With these relationships, it follows that

$$\sinh\left(\frac{2\pi d_i}{L}\right) = \left\{\frac{\pi^2(\bar{H}_s - 0.3\,\sigma)^2}{8\gamma' g D \bar{T}_s^2}\right\}^{0.5} \tag{9}$$

The value of d_i can be accurately determined using the calculator program presented in the Appendix. Alternatively, after calculating the value of the right side of equation (9), the value of $(2\pi d_i/L)$ can be determined from the graph of x versus (sinh x) in Figure 4, and converted to d_i by multiplying by $\{(L_o/2\pi)\tanh(2\pi d_i/L)\}$, using the Figure 4 graph of (tanh x) versus x. Another alternative, for $\gamma' = 1.6$, is to use the empirical approximation

$$\tilde{d}_i = (\bar{H}_s - 0.3\,\sigma)\,\bar{T}_s\,(g/5{,}000\ D)^{0.5} \tag{10}$$

which is convenient and usually within ±5 percent of an exact calculation.

Table 1 summarizes the basic procedure for calculating the water depths at the two bounds of the shoal zone, for specified values of g, γ', D, $\bar{H}_s$, σ, and $\bar{T}_s$. The procedure can be executed using either the calculator program provided in the Appendix or the graphs provided in Figures 3 and 4. A convenient alternative is to use the simple approximations in equations (6) and (10), which

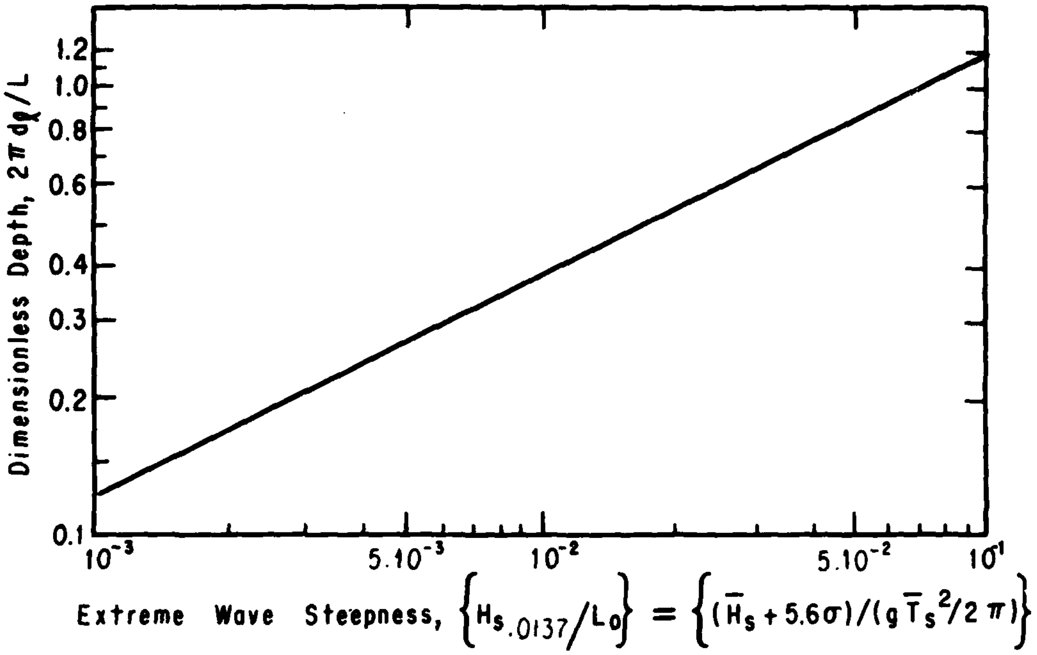

Figure 3. Graphical solution of equation (5) for $\gamma' = 1.6$.

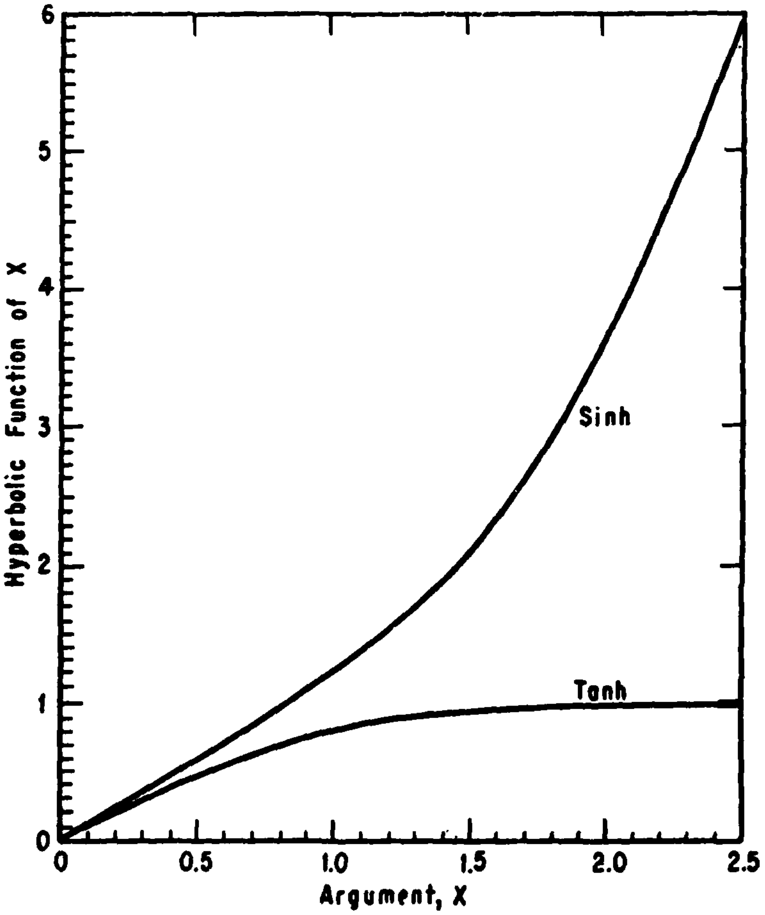

Figure 4. Graph of hyperbolic sine and tangent functions.

Table 1. Calculation procedure for locating bounds of the shoal zone.

Bound	Procedure
Landward	Required site parameters: γ' and $\bar{H}_s$, σ, $\bar{T}_s$, and g in consistent units. Find dimensionless root $(2\pi d_\ell/L)$ of equation (5), either by iteration using the calculator program in the Appendix or from Figure 3 after calculating the value of the abscissa $\{2\pi\,(\bar{H}_s + 5.6\,\sigma)/g\bar{T}_s^2\}$. Calculate $d_\ell = \left(\frac{2\pi d_\ell}{L}\right)\left\{\tanh\left(\frac{2\pi d_\ell}{L}\right)\right\}\left(\frac{g\bar{T}_s^2}{4\pi^2}\right)$.
Seaward	Additional required site parameter: D in consistent units at water depth of $(1.5\ d_\ell)$. Find the dimensionless value of $(2\pi d_i/L)$ specified by equation (9), using either the calculator program in the Appendix or Figure 4 after calculating the value of the ordinate $\left\{\frac{\pi^2\ (\bar{H}_s - 0.3\ \sigma)^2}{8\gamma' g D \bar{T}_s^2}\right\}^{0.5}$ Calculate $d_i = \left(\frac{2\pi d_i}{L}\right)\left\{\tanh\left(\frac{2\pi d_i}{L}\right)\right\}\left(\frac{g\bar{T}_s^2}{4\pi^2}\right)$.

provide results usually consistent in accuracy with the critical values given in equations (1) and (7) to one significant digit. To allow for possible effects of tides, it is recommended that the calculated d_ℓ and d_i be taken as being with respect to mean lower low water (MLLW) at a locality, giving conservative (farther seaward) locations for the shoal zone boundaries. Also, it seems appropriate to use calculated results in U.S. customary units (feet), rounded to the nearest integer unit.

III. APPLICATIONS OF d_ℓ AND d_i

The shoal zone is an objectively defined buffer area of moderate wave effects on the submerged beach profile throughout the year. Where wave and sand characteristics are known, the two calculated water depths are useful in various coastal engineering activities requiring a seaward-limit estimate. The possible applications in the following list are discussed in detail in Hallermeier (1981), and further evaluations of shoal zone uses are being conducted.

(a) Fathometer surveys of customary vertical resolution (±0.5 foot or ±0.15 meter) may not be expected to resolve usually small bottom changes during the year seaward of d_ℓ. Nearshore surveys extending to d_ℓ are needed to define seasonal conditions at a site.

(b) Gages to record waves incident on the littoral zone may be placed just seaward of the anticipated value of d_ℓ, so that the measured waves will not be modified differently through the year due to significant changes in the bottom seaward of the gage site.

(c) Sand for beach fill must be placed landward of d_ℓ to increase the sand supply in the intensely active littoral zone. The necessary quantity of nourishment material is at least that required to advance the average profile landward of d_ℓ the desired distance.

(d) In calculations of shoreline erosion due to sea level rise over long timespans, the ocean boundary to the equilibrium nearshore profile may be set at d_i.

(e) In calculations of sediment budgets pertaining to timespans less than a few decades, the ocean boundary to the control volume may be set at d_ℓ.

(f) At sites with shore-parallel contours, subaqueous borrow or disposal of material should be conducted well seaward of d_ℓ, so that destructive effects on nearshore processes are minimized. Seaward of d_ℓ, borrow or disposal might be conducted in a region with irregular contours if bottom elevations and thus shore exposure are not changed significantly.

(g) A rubble-mound breakwater should be sited in water deeper than d_ℓ for the proximate region, if its primary purpose is to provide wave shelter with minimum effect as a littoral barrier.

(h) To balance economy and function, it may be advisable to build a shore-normal structure to the length corresponding to the d_ℓ contour for the nearby region if its primary purpose is to control littoral drift.

IV. SHOAL ZONE EXTENT ALONG U.S. COASTS

Tables 2 and 3 present bounding water depths for the shoal zone at selected U.S. coastal localities. Using the calculator program provided in the Appendix, calculations for the 10 sites in Table 2 use annual summary statistics from the wave climate data reported by Thompson (1977). For these sites, at least 1 full year of nearshore surface-piercing gage data is available, with summary statistics provided by objective digital record analysis.

Table 2. Calculated shoal zone bounds for 10 U.S. sites using annual statistics of nearshore wave gage measurements (Thompson, 1977); $\gamma' = 1.6$, $g = 32.2$ feet per second squared (1 foot = 0.305 meter, 1 millimeter = 0.0033 foot).

Site	Location	$\bar{H}_s$ (ft)	σ (ft)	$\bar{T}_s$ (s)	D (mm)	d_ℓ (ft)	d_i (ft)
Atlantic coast							
Atlantic City, N.J.	39°21' N., 74°25' W.	2.95	1.55	8.6	0.11	21.5	82.0
Virginia Beach, Va.	36°51' N., 75°58' W.	2.40	1.40	8.3	0.11	19.0	65.8
Nags Head, N.C.	35°55' N., 75°36' W.	3.20	1.80	8.8	0.11	24.2	88.7
Atlantic Beach, N.C.	34°43' N., 76°44' W.	2.25	1.30	7.2	0.12	17.2	51.0
Wrightsville Beach, N.C.	34°13' N., 77°47' W.	2.60	1.10	7.7	0.11	16.3	66.7
Holden Beach, N.C.	33°55' N., 78°18' W.	2.05	1.00	7.5	0.17	14.4	43.2
Lake Worth, Fla.	26°37' N., 80°02' W.	2.10	1.15	6.7	0.21	15.4	34.8
Gulf of Mexico coast							
Naples, Fla.	26°08' N., 81°49' W.	1.10	0.75	4.6	0.12	9.1	15.8
Destin, Fla.	30°23' N., 86°25' W.	1.65	1.05	5.7	0.25	13.1	20.4
Pacific coast							
Huntington Beach, Calif.	33°39' N., 118°00' W.	2.90	1.05	13.2	0.11	17.8	139.3

Table 3. Calculated shoal zone bounds for 20 U.S. sites using annual statistics of LEO breaker observations; $\gamma' = 1.6$, $g = 32.2$ feet per second squared, $D = 0.00033$ foot (1 foot = 0.305 meter).

Site	Location	Data year	$\bar{H}_s$ (ft)	σ (ft)	$\bar{T}_s$ (s)	d_ℓ (ft)	d_i (ft)
Atlantic coast							
Assateague, Md.	38°11' N., 75°09' W.	1978	2.18	1.14	8.73	17.7	73.3
Bull Island, S.C.	32°55' N., 79°35' W.	1977-78	2.37	0.84	6.17	13.7	52.7
Tybee Lighthouse, Ga.	32°01' N., 80°50' W.	1976-77	2.80	1.85	7.30	24.3	66.7
Boca Raton, Fla.	26°22' N., 80°04' W.	1971	1.59	1.04	5.74	13.7	31.2
Gulf of Mexico coast							
St. Andrews Park, Fla.	30°05' N., 85°40' W.	1969-70	1.74	1.24	4.86	14.7	29.6
Crystal Beach, Fla.	30°23' N., 86°27' W.	1969-70	1.72	1.42	4.61	15.8	27.1
Gilchrist, Tex.	29°31' N., 94°29' W.	1975	1.29	0.95	6.55	13.3	31.4
Galveston, Tex.	29°11' N., 94°58' W.	1975	1.53	0.83	6.71	12.5	39.6
Corpus Christi, Tex.	27°45' N., 97°10' W.	1974	2.59	1.12	6.66	17.0	60.9
Pacific coast							
San Clemente, Calif.	33°24' N., 117°21' W.	1969	2.85	1.40	15.15	23.4	269.4
Bolsa Chica, Calif.	33°41' N., 118°02' W.	1969	2.42	1.23	12.10	20.0	114.4
Pt. Mugu, Calif.	34°07' N., 119°09' W.	1973	2.84	1.00	14.69	18.6	172.1
Pismo Beach, Calif.	35°09' N., 120°39' W.	1969	3.07	1.52	12.03	24.6	143.0
San Simeon, Calif.	35°34' N., 121°07' W.	1969	3.09	1.22	11.58	21.2	141.7
Capitola Beach, Calif.	36°59' N., 121°56' W.	1971	1.50	0.87	11.16	13.9	59.0
Stinson Beach, Calif.	37°54' N., 122°38' W.	1968-69	3.78	1.32	12.62	23.9	186.4
Wright's Beach, Calif.	38°24' N., 123°06' W.	1969	4.94	2.10	11.37	34.0	150.2
Shelter Cove, Calif.	40°02' N., 124°04' W.	1969-70	2.33	1.53	11.88	23.2	102.1
Prairie Creek, Calif.	41°21' N., 124°04' W.	1969-70	3.44	1.34	10.69	22.9	139.6
Umpqua, Oreg.	43°29' N., 124°13' W.	1978	3.74	1.61	9.38	25.6	172.8

Calculations for the 20 sites in Table 3 use annual summary statistics of breaker observations collected under the LEO program conducted by the U.S. Army Coastal Engineering Research Center (CERC). Such wave data are liable to criticism regarding precision and subjectivity, and seem to give larger annual mean wave heights than gages located seaward of the littoral zone. Also, for the Table 3 calculations, D has been set equal to 0.00033 foot (0.1 millimeter), a typical value. However, the Table 3 results show consistency with Table 2 results for common regions.

* * * * * * * * * * * * * * * EXAMPLE PROBLEM * * * * * * * * * * * * * * * *

GIVEN: At Galveston, Texas (29°17' N., 94°47' W.), annual wave statistics for 1966 (Thompson, 1977) are:

Mean significant height, $\bar{H}_s = 1.35$ feet

Standard deviation of height, $\sigma = 0.9$ foot

Mean wave period, $\bar{T}_s = 5.7$ seconds.

Median sediment diameter at the 18-foot water depth off Bolivar Peninsula just north of Galveston (U.S. Army Engineer District, Galveston, 1958) is:

$$D = 0.00033 \text{ foot (0.1 millimeter).}$$

FIND: The water depths d_ℓ and d_i, giving the extent of the shoal zone at this site.

SOLUTION: From equation (4),

$$H_{s0.137} = \{1.35 + (5.6)(0.9)\} = 6.4 \text{ feet},$$

and from equation (3),

$$L_o = \left\{\frac{32.2(5.7)^2}{2\pi}\right\} = 166.5 \text{ feet}$$

so that

$$\frac{H_{s0.137}}{L_o} = 0.038$$

and Figure 3 gives

$$\frac{2\pi d_\ell}{L} = 0.74$$

Figure 4 gives

$$\tanh (0.74) = 0.63,$$

so that

$$d_\ell = \left(\frac{2\pi d_\ell}{L}\right)\left(\frac{L_o}{2\pi}\right)\left\{\tanh\left(\frac{2\pi d_\ell}{L}\right)\right\} = (0.74)(26.5)(0.63) = 12.4 \text{ feet} \simeq 12 \text{ feet}.$$

Note that equation (6) gives

$$\tilde{d}_\ell = \{2[1.35 + 11(0.9)]\} = 12.6 \text{ feet} \simeq 13 \text{ feet}.$$

From equation (8) ,

$$H_{s50} = \{1.35 - 0.3(0.9)\} = 1.08 \text{ feet},$$

so equation (9) becomes

$$\sinh\left(\frac{2\pi d_i}{L}\right) = \left\{\frac{\pi^2(1.08)^2}{8(1.6)(32.2)(0.00033)(5.7)^2}\right\}^{0.5} = 1.61$$

Figure 4 gives

$$\sinh^{-1}(1.61) \approx 1.26 = \left(\frac{2\pi d_i}{L}\right)$$

and

$$\tanh\left(\frac{2\pi d_i}{L}\right) = 0.85,$$

so that

$$d_i = \left(\frac{2\pi d_i}{L}\right)\left(\frac{L_o}{2\pi}\right)\left[\tanh\left(\frac{2\pi d_i}{L}\right)\right] = (1.26)(26.45)(0.85) = 28.33 \text{ feet} \simeq 28 \text{ feet}.$$

Note that equation (10) gives

$$\tilde{d}_i = \{(1.08)(5.7)[32.25/5{,}000(0.00033)]^{0.5}\} = 27.2 \text{ feet} \simeq 27 \text{ feet}.$$

With the same input parameters, the calculator program in the Appendix gives the more precise results:

$$d_\ell = 12.30 \text{ feet} \simeq 12 \text{ feet}$$

$$d_i = 28.32 \text{ feet} \simeq 28 \text{ feet}.$$

* *

These calculated results are to be considered in conjunction with other possible indicators of the seaward limit to the wave-dominated profile. Everts (1978) reported two geometric limit depths for Palm Beach near the center of Galveston Island (29°12' N., 94°57' W.). The limit depth to shore-parallel bathymetry is 47 feet (14.3 meters), and the depth at the boundary between the shoreface and ramp profile sectors is 59 feet (18.0 meters); both depths are with respect to mean low water (MLW).

Sand-size variation along the profile can indicate a seaward limit to wave effects (U.S. Army, Corps of Engineers, Coastal Engineering Research Center, 1977). For the Galveston area, Fisher, et al. (1972) charted the boundary between "shoreface sand and muddy sand" and "shelf mud and sand with shell" at about 28 to 29 feet below mean sea level (MSL). (MLW is about 1 foot below MSL at this site.)

Watson and Behrens (1976) presented six profiles surveyed to about 14 feet below MSL in June and December 1974 and March 1976 near New Corpus Christi Pass, Texas (28°41' N., 97°11' W.). Five of these profiles superpose to within ±0.5 foot beyond a water depth of about 10 to 12 feet below MLW. Charted profile geometry at this site is similar to that near Galveston (Everts, 1978), and wave climate may be expected to be similar.

The preceding information supports the calculated values of d_i and d_ℓ for this site. In this example, the shoal zone seems well-founded, while the two geometric indicators derived by Everts (1978) are not supported by other evidence on the limits to wave effects on the submarine profile.

V. SUMMARY

This report is a self-contained presentation of the calculation procedure (Table 1) for locating a shoal zone along a sand beach profile. The water depths bounding this shoal zone depend on sand characteristics (γ', D) and summary statistics of annual wave climate ($\bar{H}_s$, σ, and $\bar{T}_s$). The shoal zone is defined so that expected surface waves have only moderate effects on the sand bottom in this zone throughout a typical year. The calculated shoal zone bounds have applications in coastal engineering activities requiring an estimate of the seaward limit to the wave-dominated nearshore region (see Sec. III).

The assumptions involved in the shoal zone model are limiting, to some extent, and confirmatory field evidence is definitely meager, but the present calculation procedure is objective, and seems to be a useful new tool for engineering applications. The calculated shoal zone supplements other estimation techniques for the seaward limit (U.S. Army, Corps of Engineers, Coastal Engineering Research Center, 1977); of these other techniques, analysis of sediment character variation along the profile seems the most defendable.

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APPENDIX

CALCULATOR PROGRAM FOR THE BOUNDS OF THE SHOAL ZONE

A calculator program executing the Table 1 procedure is documented on the following four pages. Written for the Hewlett-Packard HP-67 Programmable Pocket Calculator, this program uses metric or U.S. customary units, 224 program steps, 25 storage registers, and RPN logic. The program could be translated for use with calculators having other logic systems and similar features and capacities.

The program incorporates the basic relationships in equations (1) and (7), the needed identities for hyperbolic functions and for linear waves, and an effective interative root-finding routine. The parameters to be specified for the calculations are $\bar{H}_s$, σ, $\bar{T}_s$, D, γ', and g. For quartz sand, $\gamma' \simeq 1.6$ in seawater and $\gamma' = 1.65$ in freshwater, with slight variations with water temperature and, of course, salinity (Komar, 1976). For most sites, especially at sea level in temperate latitudes, the value of g may be taken to be 32.2 feet (981 centimeters) per second squared.

Program Description

Program Title BOUNDING WATER DEPTHS OF WAVE-BASED SHOAL ZONE
Name ROBERT J. HALLERMEIER **Date** Jan. 1981
Address RESEARCH DIVISION, U.S. ARMY COASTAL ENGINEERING RESEARCH CENTER
City KINGMAN BUILDING, FORT BELVOIR **State** VIRGINIA **Zip Code** 22060

Program Description, Equations, Variables, etc. THE MAIN PROGRAM PERFORMS AN ITERATIVE SOLUTION OF TWO FUNCTIONS DEFINING DIMENSIONLESS WATER DEPTH AT EACH END OF A SHOAL ZONE ALONG THE SUBMERGED BEACH PROFILE. AFTER WAVE AND SAND CHARACTER AT A SITE ARE INPUT, THE SECANT METHOD FINDS A ROOT ACCURATE TO THREE SIGNIFICANT FIGURES. OTHER PROGRAMS: CONVERT THE DIMENSIONLESS ROOTS TO d_ℓ AND d_i, WATER DEPTHS IN METERS AT THE LANDWARD AND SEAWARD BOUNDARIES, RESPECTIVELY; PERFORM UNITS CONVERSIONS; AND CALCULATE CRITICAL VELOCITY, v_c, FOR SAND MOTION INITIATION. OTHER SYMBOLS ARE:
γ' = RATIO OF DENSITY DIFFERENCE BETWEEN SAND AND FLUID TO FLUID DENSITY;
$\overline{T}_s$ = ANNUAL AVERAGE SIGNIFICANT WAVE PERIOD; g = ACCELERATION OF GRAVITY;
$\overline{H}_s$ = ANNUAL AVERAGE SIGNIFICANT WAVE HEIGHT; D = CHARACTERISTIC SAND SIZE;
σ = ANNUAL STANDARD DEVIATION OF SIGNIFICANT WAVE HEIGHT; L = LOCAL WAVELENGTH;
a = NEAR-BOTTOM HORIZONTAL FLOW AMPLITUDE; $L_0 = (gT^2/2\pi)$ = DEEP-WATER WAVELENGTH;
$\xi_x = (2\pi d_x/L)$ = DIMENSIONLESS WATER DEPTH; x = DUMMY INDEX STANDING FOR ℓ OR i.

THE TWO BASIC FUNCTIONS ARE:

$$0 = \xi_\ell (e^{-\xi_\ell} - e^{\xi_\ell})^3 + \frac{4\pi^2}{0.03\,\gamma'} \frac{(\overline{H}_s + 5.6\sigma)^2}{L_0^2} (e^{\xi_\ell} + e^{-\xi_\ell}) \qquad \text{[LBL 2]}$$

AND

$$0 = 1 + \{a(e^{-\xi_i} - e^{\xi_i})/(\overline{H}_s - 0.3\,\sigma)\} \,. \qquad \text{[LBL 3]}$$

THE SECANT METHOD USES THE ITERATION EQUATION:

$$\xi_{j+1} = \xi_j - F(\xi_j)\{(\xi_j - \xi_{j-1})/[F(\xi_j) - F(\xi_{j-1})]\} \,. \qquad \text{[LBL E]}$$

OTHER EQUATIONS AND IDENTITIES EMPLOYED ARE:

$$a_x = H_x/2 \sinh \xi_x \;;\; v_c = 2\pi a/T = (8\gamma' g D)^{0.5} \quad \text{[LBL C]};$$

$$\sinh \xi_x = \tfrac{1}{2}(e^{\xi_x} - e^{-\xi_x}) \;;\; \tanh \xi_x = (e^{\xi_x} - e^{-\xi_x})/(e^{\xi_x} + e^{-\xi_x});$$

$$L_0(\tanh \xi_x) = L \;;\; d_x = (\xi_x \tanh \xi_x)(L_0/2\pi) \,.$$

Operating Limits and Warnings THE INCORPORATED BASIC RESULTS ARE VALID ONLY FOR OPEN-COAST CONDITIONS AND SAND-SIZE SEDIMENTS (D BETWEEN 0.006 AND 0.2 CENTIMETERS). LINEAR WAVE THEORY AND A MODIFIED EXPONENTIAL DISTRIBUTION FOR CUMULATIVE WAVE HEIGHT ARE ASSUMED. THE ROOTS ξ_ℓ AND ξ_i CAN BE PHYSICALLY MEANINGFUL ONLY IF THEY ARE BETWEEN 0.1 AND 3.0, APPROXIMATELY.

User Instructions

BOUNDING WATER DEPTHS OF WAVE-BASED SHOAL ZONE

1 2A: landward bound, ξ_ℓ C: critical velocity calculation $\hat{\xi}$ E: start root finder 2

3A: seaward bound, ξ_i

fa: if feet used fb: ξ_ℓ → meters fd: ξ_i → meters fe: meters → feet

STEP	INSTRUCTIONS	INPUT DATA/UNITS	KEYS		OUTPUT DATA/UNITS
1	LOAD PROGRAM INTO CALCULATOR MEMORY.				
2	STORE SITE PARAMETERS:				
	i. NORMALIZED IMMERSED SEDIMENT DENSITY	γ', –	STO	0	
	ii. ANNUAL AVERAGE SIGNIFICANT WAVE PERIOD	$\bar{T}_s$, sec	STO	1	
	iii. ANNUAL AVERAGE SIGNIFICANT WAVE HEIGHT	$\bar{H}_s$, m	STO	2	
		$\bar{H}_s$, Ft	STO	3	
	iv. ANNUAL STANDARD DEVIATION OF HEIGHT	σ, m	STO	4	
		σ, Ft	STO	5	
	v. ACCELERATION OF GRAVITY.	g, cm/sec^2	STO	6	
		g, Ft/sec^2	STO	7	
3	IF ANY INPUT PARAMETER IS IN NON-METRIC				
	UNITS, AND/OR OUTPUTS ARE WANTED IN NON-		f	a	
	METRIC UNITS, ENGAGE CONVERSION PROGRAM.				
4	EXCHANGE PRIMARY/SECONDARY REGISTER CONTENTS.		f	P⇄S	
5	CALL LANDWARD BOUND FUNCTION (ξ_ℓ).		2	A	
6	GUESS $\xi_\ell = 0.6$ AND BEGIN ITERATION.		.		
			6		
			E		
7	WAIT FOR STATIONARY DISPLAY OF ξ_ℓ ROOT.				ξ_ℓ, –
8	CONVERT ξ_ℓ TO d_ℓ IN METERS AND STORE.		f	b	d_ℓ, m
9	IF DESIRED, CONVERT d_ℓ TO FEET.		f	e	d_ℓ, Ft
10	EXCHANGE PRIMARY/SECONDARY REGISTER CONTENTS.		f	P⇄S	
11	STORE ADDITIONAL SITE PARAMETER:				
	vi. SAND SIZE AT WATER DEPTH OF ($1.5 d_\ell$)	D, cm	STO	8	
12	EXCHANGE PRIMARY/SECONDARY REGISTER CONTENTS		f	P⇄S	
13	ENGAGE PROGRAM TO CALCULATE AND STORE		C		
	CRITICAL VELOCITY FOR SAND MOTION INITIATION.				
14	WAIT FOR STATIONARY DISPLAY OF CRITICAL VELOCITY				v_c, m/sec
15	CALL SEAWARD BOUND FUNCTION (ξ_i).		3	A	
16	GUESS $\xi_i = 1.2$ AND BEGIN ITERATION.		1		
			.		
			2		
			E		
17	WAIT FOR STATIONARY DISPLAY OF ξ_i ROOT				ξ_i, –
18	CONVERT ξ_i TO d_i IN METERS AND STORE.		f	d	d_i, m
19	IF DESIRED, CONVERT d_i TO FEET		f	e	d_i, Ft
20	FOR NEW CASE, CLEAR ALL REGISTERS		f	CL REG	
	AND RETURN TO STEP 2.		f	P⇄S	
			f	CL REG	

Program Listing

STEP	KEY ENTRY	KEY CODE	COMMENTS	STEP	KEY ENTRY	KEY CODE	COMMENTS
001	g LBL f a	32 25 11	UNITS CONVERSION		DSP 3	23 03	
	3	03	AND STORAGE.		F GSB B	31 22 12	
	0	00			RCL B	34 12	
	.	83		060	GTO 0	22 00	
	4	04			F LBL 6	31 25 06	
	8	08			RCL 0	34 00	
	STO 9	33 09			F GSB (i)	31 22 24	
	RCL 3	34 03			STO B	33 12	
	f x=0	31 51			f LBL 0	31 25 00	
010	GTO 5	22 05			RCL A	34 11	
	F %	31 82			RCL 0	34 00	
	STO 2	33 02			STO A	33 11	
	f LBL 5	31 25 05			−	51	
	RCL 9	34 09		070	RCL D	34 14	
	RCL 5	34 05			RCL B	34 12	
	f x=0	31 51			STO D	33 14	
	GTO 7	22 07			−	51	
	f %	31 82			÷	81	
	STO 4	33 04			x	71	
020	F LBL 7	31 25 07			STO − 0	33 51 00	
	RCL 9	34 09			RCL 0	34 00	
	RCL 7	34 07			÷	81	
	F x=0	31 51			f RND	31 24	
	h RTN	35 22		080	f x≠0	31 61	
	x	71			GTO 6	22 06	
	STO 6	33 06			RCL 0	34 00	
	h RTN	35 22			h RTN	35 22	
	F LBL A	31 25 11	STORE FUNCTION		f LBL C	31 25 13	CALCULATE AND
	h STO I	35 33	NUMBER.		f P⇄S	31 42	STORE CRITICAL
030	h RTN	35 22			RCL 0	34 00	VELOCITY.
	F LBL B	31 25 12	FINITE - DIFFERENCE		RCL 6	34 06	
	EEX	43	APPROXIMATION FOR		x	71	
	CHS	42	FIRST DERIVATIVE.		RCL 8	34 08	
	2	02		090	x	71	
	F %	31 82			f √x	31 54	
	STO C	33 13			8	08	
	2	02			f √x	31 54	
	÷	81			f %	31 82	
	−	51			f P⇄S	31 42	
040	STO A	33 11			STO 9	33 09	
	STO 0	33 00			h RTN	35 22	
	F GSB (i)	31 22 24			f LBL 2	31 25 02	DIMENSIONLESS
	STO D	33 14			g e^x	32 52	LANDWARD BOUND
	RCL A	34 11		100	STO 4	33 04	FUNCTION.
	RCL C	34 13			h 1/x	35 62	
	+	61			RCL 4	34 04	
	STO 0	33 00			+	61	
	F GSB (i)	31 22 24			STO 8	33 08	
	STO B	33 12			RCL 3	34 03	
050	RCL D	34 14			f x=0	31 61	
	−	51			GTO 4	22 04	
	RCL C	34 13			2	02	
	÷	81			h π	35 73	
	h RTN	35 22		110	x	71	
	F LBL E	31 25 15	ITERATIVE SECANT		STO 5	33 05	
	F FIX	31 23	ROOT FINDER.		f P⇄S	31 42	

REGISTERS

0 ξ_j	1 d_l (m)	2 d_i (m)	3 L_o (m)	4 used	5 2π	6 used	7 used	8 used	9 V_c (m/sec)
S0 γ'	S1 T_s (sec)	S2 H_s (m)	S3 H_s (Ft)	S4 σ (m)	S5 σ (Ft)	S6 g (cm/sec²)	S7 g (Ft/sec²)	S8 D (cm)	S9 30.48

A ξ_{j-1}	B $F(\xi_j)$	C $\Delta\xi_j$	D $F(\xi_{j-1})$	E	I Function number

STEP	KEY ENTRY	KEY CODE	COMMENTS
	RCL 1	34 01	
	g x^2	32 54	
	RCL 6	34 06	
	f %	31 82	
	f P⇄S	31 42	
	RCL 5	34 05	
	÷	81	
120	STO 3	33 03	
	f LBL 4	31 25 04	
	f P⇄S	31 42	
	RCL 4	34 04	
	5	05	
	.	83	
	6	06	
	×	71	
	RCL 2	34 02	
	+	61	
130	f P⇄S	31 42	
	RCL 3	34 03	
	÷	81	
	g x^2	32 54	
	RCL 5	34 05	
	g x^2	32 54	
	×	71	
	.	83	
	0	00	
	3	03	
140	÷	81	
	f P⇄S	31 42	
	RCL 0	34 00	
	÷	81	
	f P⇄S	31 42	
	STO 6	33 06	
	RCL 8	34 08	
	STO × 6	33 71 06	
	RCL 4	34 04	
	h $1/x$	35 62	
150	RCL 4	34 04	
	−	51	
	STO 7	33 07	
	3	03	
	h y^x	35 63	
	RCL 0	34 00	
	×	71	
	STO + 6	33 61 06	
	RCL 6	34 06	
	h RTN	35 22	
160	g LBL f b	32 25 12	CONVERT LANDWARD
	RCL 7	34 07	BOUND TO METERS.
	CHS	42	
	RCL 8	34 08	
	÷	81	
	RCL 0	34 00	
	×	71	
	RCL 3	34 03	
	×	71	

STEP	KEY ENTRY	KEY CODE	COMMENTS
	RCL 5	34 05	
170	÷	81	
	STO 1	33 01	
	h RTN	35 22	
	f LBL 3	31 25 03	DIMENSIONLESS
	g e^x	32 52	SEAWARD BOUND
	STO 4	33 04	FUNCTION.
	h $1/x$	35 62	
	RCL 4	34 04	
	−	51	
	RCL 5	34 05	
180	h $1/x$	35 62	
	f P⇄S	31 42	
	RCL 1	34 01	
	×	71	
	RCL 4	34 04	
	.	83	
	3	03	
	×	71	
	CHS	42	
	RCL 2	34 02	
190	+	61	
	÷	81	
	f P⇄S	31 42	
	RCL 9	34 09	
	×	71	
	STO 6	33 06	
	×	71	
	1	01	
	+	61	
	h RTN	35 22	
200	g LBL f d	32 25 14	CONVERT SEAWARD
	RCL 4	34 04	BOUND TO METERS.
	h $1/x$	35 62	
	RCL 4	34 04	
	+	61	
	RCL 6	34 06	
	×	71	
	h $1/x$	35 62	
	RCL 3	34 03	
	×	71	
210	RCL 0	34 00	
	×	71	
	RCL 5	34 05	
	÷	81	
	STO 2	33 02	
	h RTN	35 22	
	g LBL f e	32 25 15	CONVERT BOUNDS
	f P⇄S	31 42	FROM METERS TO
	RCL 9	34 09	FEET.
	f %	31 82	
220	1	01	
	g 10^x	32 53	
	×	71	
	f P⇄S	31 42	
	h RTN	35 22	

LABELS

A Function	B First derivative	C critical velocity	D	E secant root-finder
a Input units conversion	b $\xi_L \to d_L(m)$	c	d $\xi_i \to d_i(m)$	e Output units conversion
0 used	1	2 ξ_L Function	3 ξ_i Function	4 used
5 used	6 iterate	7 used	8 used	9

FLAGS

0	
1	
2	
3	

SET STATUS

FLAGS			TRIG		DISP	
	ON	OFF				
0	☐	☒	DEG	☒	FIX	☒
1	☐	☒	GRAD	☐	SCI	☐
2	☐	☒	RAD	☐	ENG	☐
3	☐	☒			n	3

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