CHAPTER 6

Channel Depth

6-1. Depth Design. The depth of the project design channel should be adequate to safely accommodate ships with the deepest drafts expected to use the waterway and call at the project port on a frequent and continuing basis. Normally, the project depth is based on the development of one or more design ships with an appropriately loaded or ballasted draft. Selection of the design ship and project design depth is determined jointly by an economic analysis of the expected project benefits compared with project costs. Once the design ship and channel depth are determined, the safety and adequacy of the channel depth for operational design ship transits will be determined using the analysis presented later in this chapter. The channel depth economic analysis is described in ER 1105-2-100. Paragraph 6-2 summarizes the procedure with an emphasis on applications to deep-draft navigation channels.

The design depth of the channel need not be constant throughout the project but may vary as necessary so that the design ship will be able to make a safe, efficient, and cost-effective transit of the channel under normal operational conditions. Upon project authorization, the design depths are considered, nominally, to be the authorized depths. This should not preclude minor adjustments in depth during continued design, construction, and operation as circumstances warrant and delegated authorities permit.

6-2. Economic Analysis.

a. *Optimization.* The optimum design of a deep-draft navigation project requires studies of estimated costs and benefits of various plans and alternative designs considering safety, efficiency, and environmental impacts. These studies are used to determine the most economical and functional channel alignment and design depth considering costs for various alternative designs. Generally, several alternative channel depth design levels are developed, since depth is often one of the major cost-determining parameters. The adaptability of each design to future improvements for increased navigational capability should also be considered. Economic optimization analysis should consider various elements involved in development and maintenance of the project, including dredging, disposal, and structures such as jetties, breakwaters, and aids to navigation. The optimum economic channel is selected from a comparison of annual benefits and annual costs for each channel plan.

b. *Project Cost.* The economic optimization of a channel requires selection of several design alignments and dimensions (width and depth) that are acceptable for safe and efficient navigation. Costs are developed for the alternative plan alignments and dimensions. These should include:

(1) Initial construction including fixed facilities cost.

(2) Replacement cost.

(3) Operation and maintenance cost.

c. Project Benefits. Benefits are determined by transportation savings considering ship trip time and cargo capacity and delays for tides, weather conditions, and transit interference from reduced depths in channels that have rapid shoaling tendencies. Deeper channels will permit the use of larger ships, which are more economical to operate. Some ships could use the channel with a deeper draft and greater cargo loading and may eliminate or reduce the need for offloading (lighterage) some of the cargo before proceeding to the port. Benefits are evaluated by determining the transportation costs per ton of commodity for each increment of channel depth. This evaluation has to consider the trends in shipbuilding to determine the most likely future ship sizes and an estimate of the future ship fleet that will be using the channel. Transportation costs are based on ship annual operating cost for each type of ship, including fixed cost and annual operating expenses. The HQUSACE Water Resources Support Center periodically releases ship operating cost data for evaluating deep-draft channel and harbor improvement projects.

d. Evaluation Procedure. The basic economic benefits from navigation projects are the reduction of costs required to transport commodities and the increase in the value of output for goods and services. Benefits are usually derived based on costs reduced or not incurred with the proposed project improvements. Project benefits may also be “lost opportunity” costs because of unimproved or undeveloped navigation channels. Specific transportation savings may result from the following:

(1) More efficient use of larger ships.

(2) More efficient use of present ships.

(3) Reductions in transit or delay times.

(4) Reduction of cargo handling costs.

(5) Reduction of tug assistance costs.

(6) Reduction of insurance, interest, and storage costs.

(7) Use of water rather than land transport mode.

(8) Reduction of accident rate and cost of damage.

The evaluation procedure to estimate navigation benefits includes nine individual steps shown on the flowchart (Figure 6-1). The key step in the procedure is the accurate projection of commodity movements over the proposed alternative project designs, steps 3 and 7. Details of the procedure are given in ER 1105-2-100.

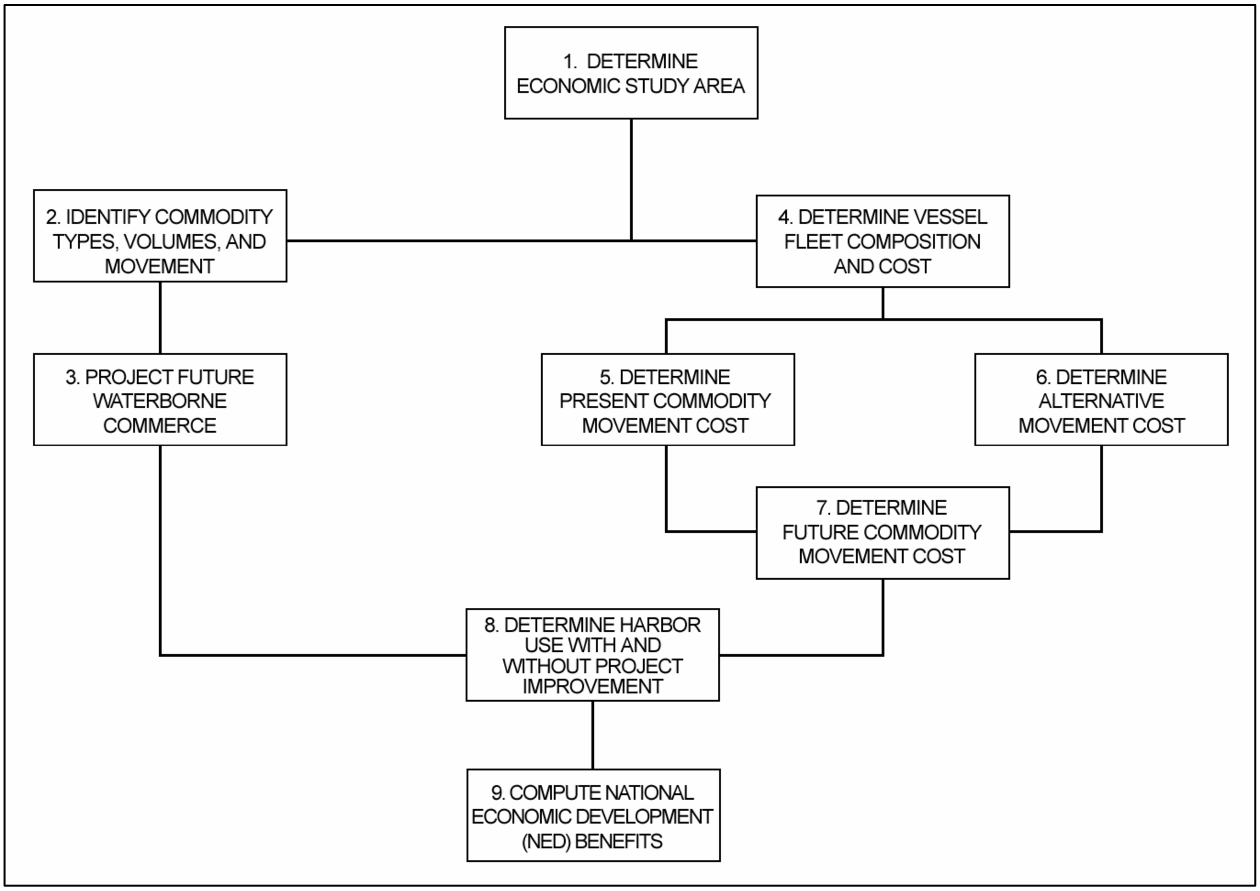

Figure 6-1. Navigation benefit evaluation procedure

6-3. Ship Squat

a. Introduction. A ship in motion will be lowered (ship sinkage) vertically below the still water surface because of the increased velocity past the ship causing the pressure on the ship hull to be decreased. This phenomenon occurs in deep, open-water situations, such as out at sea as well as in shallow water. However, the effect is greatly increased in shallow, restricted water, such as a canal- or trench-type open navigation channel. The running trim of a ship is also modified by the pressure on the ship hull: blunt-bowed ships tend to be lowered by the bow (i.e., at the bow), while fine-lined ships are trimmed by the stern. Ship squat is a well-known phenomenon by seamen, and efforts to estimate the effect have been used by pilots for many years. However, many of these techniques are often based on crude approximations or are site-specific, and usually couched in general rules for use by pilots. The following presents a general calculation procedure for use in channel design in shallow water, in canals, and in trench channels with channel banks.

b. Shallow-Water Squat. Total ship vertical response in shallow water from speed ahead in a laterally unrestricted waterway was derived by Tuck and Taylor (1970) using ship slender body theory and put into practical use by Huuska (1976). The ship sinkage and running trim equations are given by the following:

$$\frac{z}{L} = C_Z \frac{F_h^2}{\sqrt{1-F_h^2}} \frac{\nabla}{L^3} \qquad (6\text{-}1)$$

$$\Theta = C_\Theta \frac{F_h^2}{\sqrt{1-F_h^2}} \frac{\nabla}{L^3} \qquad (6\text{-}2)$$

where

z = sinkage or vertical drop of ship center of gravity in meters (feet)

L = ship length in meters (feet)

C_z = sinkage coefficient characteristic of hull form .1.5

Λ = volume displacement of the ship in cubic meters (cubic feet) (Figure 3-3)

Θ = trim angle of ship in radians, positive is bow up

C_Θ = trim coefficient characteristic of hull form .1.0

F_h = channel depth Froude number (Equation 4-2)

Typical values of the two coefficients, which have been determined by experiments and calculations, are 1.5 and 1.0. For channel design purposes, the maximum vertical ship motion below the vessel's static position may be found from the combination of Equations 6-1 and 6-2 to give the ship squat as follows (Norrbin 1986, Rekonen 1980):

$$\frac{z_{\max}}{T} = 2.4 \frac{C_B}{L/B} \frac{F_h^2}{\sqrt{1-F_h^2}} \qquad (6\text{-}3)$$

where

$z_{\max}$ = ship squat (sinkage and trim) at bow or stern in meters (feet)

T = ship full load molded draft in meters (feet)

$C_B = \frac{\nabla}{LBT}$

B = ship molded beam at the maximum section area in meters (feet)

c. Simplified Equation. The combined ship vertical movement resulting from sinkage and trim (the squat) may be calculated by the following simple relation presented by Norrbin (1986), to be used when Froude numbers are less than 0.4:

$$z_{\max} = \frac{C_B BTV^2}{15Lh}$$

where z_{max} is in meters and V is in knots. Adjusting this relation for z_{max} in meters (feet) yields

$$z_{\max} = \frac{C_B BTV^2}{4.573Lh} \quad (6\text{-}4)$$

This equation shows that the amount of squat depends on several factors, including the square of the ship speed, depth of the channel, and geometric characteristics of the ship.

d. *Example.* As an example application, for tankers the following values are typical: $C_B = 0.85$, and $L/B = 6.5$. A channel depth-to-ship draft ratio (h/T) of 1.1 is also typical for harbor channels. With these values, the following equation is thus obtained:

$$z_{\max} = 0.026V^2 \quad (6\text{-}5)$$

For a ship speed of 5 knots (2.6 m/sec (8.4 ft/sec)), this gives z_{max} = 0.2 m (0.63 ft); and for a ship speed of 10 knots (5.1 m/sec (16.8 ft/sec)), z_{max} = 0.8 m (2.6 ft). These results suggest that an increase in channel depth of about 0.3 m (1 ft) may be needed for ship maneuvering in wide channels with deep overbank areas where ship speeds are 6 knots or less. For harbor fairway or entrance channels without channel banks, where ship speeds are typically high, i.e., near 10 knots, channel underkeel clearance of 0.8 m (2.6 ft) or more would normally be required.

e. *Restricted Channel Squat.* A ship sailing in a canal or trench navigation channel will cause the water surface elevation to be lowered because of the increased velocity past the ship due to the Bernoulli effect. A one-dimensional (1-D) approximation (sometimes called the canal theory), which has been reviewed in many publications (Blaauw and van der Knaap 1983), can be used to develop graphical or computer-based computational methods to calculate the resulting water level depression or drawdown. The lowering of the water level is equal to the mean ship sinkage and therefore the squat. Ship squat in a restricted channel depends especially on the ship speed, varying as the square of the speed. Other factors are also important, including the channel cross-sectional characteristics and the ship geometry. The simple canal theory used to calculate squat depends on certain flow assumptions as presented in Figure 6-2. The assumption of a rectangular channel cross section is especially limiting since real channels are generally trapezoidal and often become irregularly shaped over time. Many channels are of the trench type with overbank depths on each side of the channel, which further complicate the computations and would tend to reduce the squat. Nevertheless, this simple model provides useful design guidance showing the main parameters and their functional relationships. An outlined derivation of the numerical method is shown in Figure 6-3. The reader should refer to Figure 6-2 for explanation of parameters in the derivation.

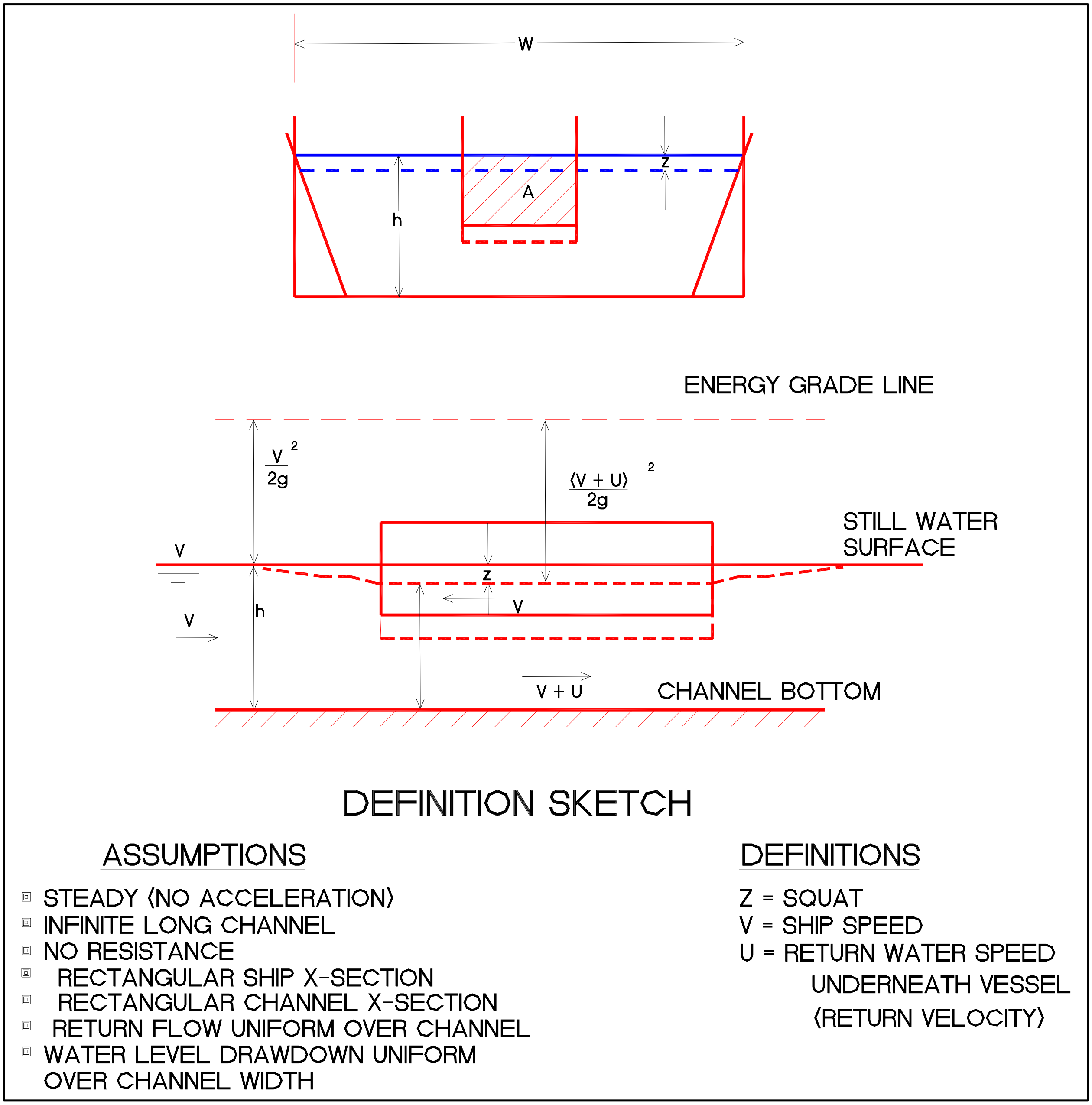

Figure 6-2. Squat analysis definition

f. *Limiting Conditions.* An important parameter for characterizing the ship's interaction with the water flow generated by the ship in the navigation channel is the ship speed. In particular, as previously discussed in Chapter 4, the ship speed in a given channel is limited by a parameter called the Schijf limiting speed. Self-propelled ships cannot exceed this limit; indeed, for economic reasons, maximum ship speeds are well below this speed (about 80 percent). The value of the Schijf limiting Froude number can be calculated using the following explicit formula (Huval 1980b, Balanin et al. 1977, Zernov 1970):

Bernoulli=s: $h+\frac{V^2}{2g}=h-z+\frac{(V+U)^2}{2g}$ (1)

Continuity: $WhV=(Wh-A_S-Wz)(V+U)$ (2)

Simplify Equation (1): $\frac{V^2}{2g}=\frac{(V+U)^2}{2g}-z$ (3)

Multiply by 2 and divide by h:

$$\frac{V^2}{gh}=\frac{(V+U)^2}{gh}-2\frac{z}{h} \quad (4)$$

Rearrange Equation (2):

$$V+U=\frac{V}{\left(1-\frac{A_S}{Wh}-\frac{z}{h}\right)} \quad (5)$$

Substitute Eqn (5) into (4), and calling $\frac{V^2}{gh}=F_h^2$:

$$F_h^2=\frac{F_h^2}{\left(1-\frac{A_S}{Wh}-\frac{Z}{h}\right)^2}-2\frac{z}{h} \quad (6)$$

Divide by F_h^2 and rearrange:

$$\frac{2z}{F_h^2 h}=\frac{1}{\left(1-\frac{A_S}{Wh}-\frac{z}{h}\right)^2}-1 \quad (7)$$

Simplify:

$$F_h=\sqrt{\frac{2\frac{z}{h}\left(1-\frac{A_S}{Wh}-\frac{z}{h}\right)^2}{1-\left(1-\frac{A_S}{Wh}-\frac{z}{h}\right)^2}} \quad (8)$$

Figure 6-3. Squat analysis definition

$$F_{hL}=\sqrt{8\cos^3\left(\frac{\pi}{3}+\frac{\arccos}{3}\left(1-\frac{1}{B_R}\right)\right)}$$

Furthermore, (6-6)

$$F_{hL}=\frac{V_L}{\sqrt{gh}}$$

where

F_{hL} = depth Froude number at limiting ship speed

V_L = Schijf limiting ship speed

B_R = blockage ratio (cross-sectional area of the channel divided by the cross-sectional area of the ship)

The ship limiting speed can readily be obtained from the Froude number for a given channel water depth.

g. Limiting Squat. It is also possible to relate the maximum ship squat at the Schijf limiting Froude number by the equation

$$z_L = \frac{F_{hL}^2}{2}\left(F_{hL}^{1/3} - 1\right)h \tag{6-7}$$

In a similar fashion, the return velocity Froude number is

$$\frac{U_L}{\sqrt{gh}} = F_{hL}^{1/3} - F_{hL} \tag{6-8}$$

where

U_L =limiting return velocity

z_L =squat at limiting ship speed.

h. Computer Model. The solution to the general equations for squat and return velocity may be obtained by an approximation method involving iteration which can be programmed on a calculator or computer (Huval 1993). An approximate analysis for nonrectangular channel cross sections can be made by replacing the channel depth *h* by the cross-sectioned mean depth, which is equal to the channel area divided by the top width, $d = A_c /W$. A more complete analysis for trapezoidal channels has also been presented.

i. Computational Procedure. Most navigation channels are dredged over a wide waterway with variable overbank depths on each side of the channel, called trench channels. Figure 6-4 gives example navigation channel cross sections. A first approximation to the ship squat for trench channels may be made bycalculating the weighted average (based on overbank depth) of squat in shallow water and in canal-type channel without the overbanks. This type of trench channel has been tested for ship squat by Guliev (1971) and has been implemented in a calculation procedure developed by Huuska (1976) and adopted for this manual. This more complete squat calculation model applicable for shallow water, canals, and trench-type channels has been developed as a software program on a computer and is available from Huval (1993). The results of computations using this model are presented in Figure 6-5.

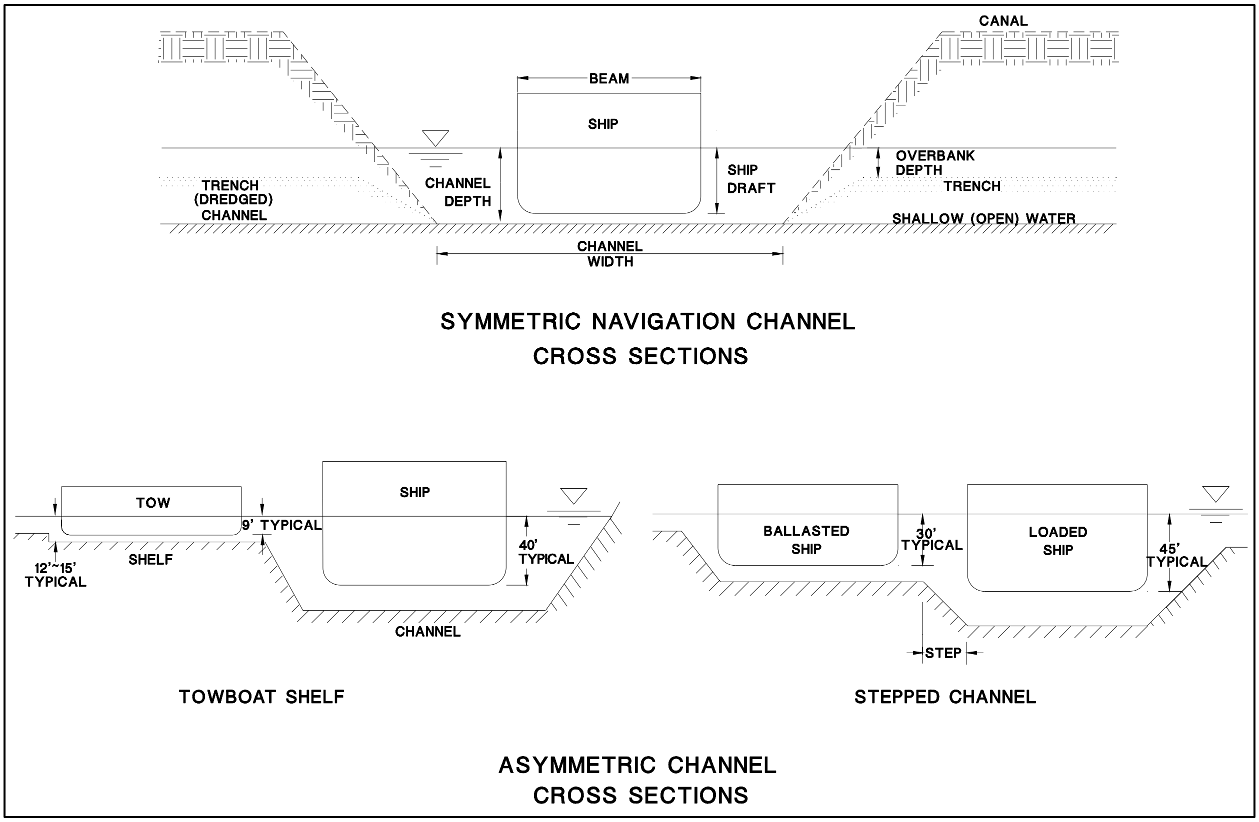

Figure 6-4. Channel cross sections

6-4. Ship Motion in Waves.

a. Ship Response. Ship response from waves is a factor that must be considered in the design of navigation channel depths and widths. The movement of the ship bottom below the static water surface caused by waves will affect the design of channel depth. Usually, wave effects are more pronounced and important in the design of the entrance channel or harbor fairway, which is open to ocean waves leading from the ocean into a bay or river with a port. Wave effects on commercial ships transiting entrance channels tend to increase as the wave heights increase and decrease with longer ship lengths. Maximum ship response occurs with wavelengths equal to or nearly equal to the ship length. Normal commercial deep-draft design ships will respond very weakly to wave periods less than 6 sec, mainly a result of the fact that natural ship periods are much greater.

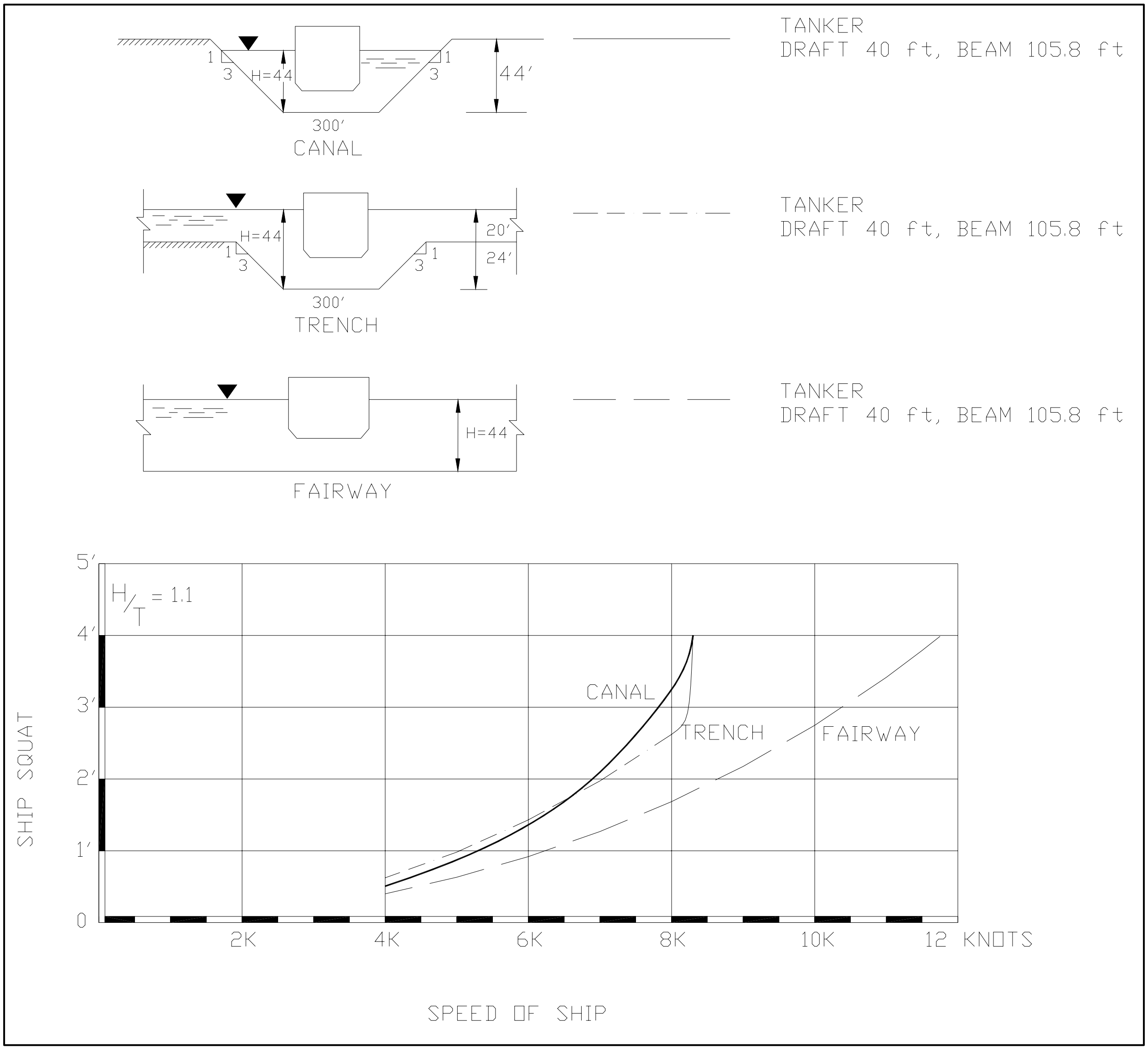

Figure 6-5. Example squat calculations

b. Roll, Pitch, and Heave. Ships will respond to waves by the vertical motions of roll, pitch, and heave from local seas and swell in harbor entrance channels. Figure 6-6 presents a definition sketch of the six possible modes of ship response to wave action. The vertical ship motion should be used in setting the vertical depth in the entrance channel above the depth in the interior harbor channels. The magnitude of the vertical motion of a ship transiting a harbor fairway is a function of many factors, some of which include:

(1) Sea or swell conditions.

(2) Wave height, period, and duration.

(3) Direction and celerity of wave propagation.

(4) Ship transit direction.

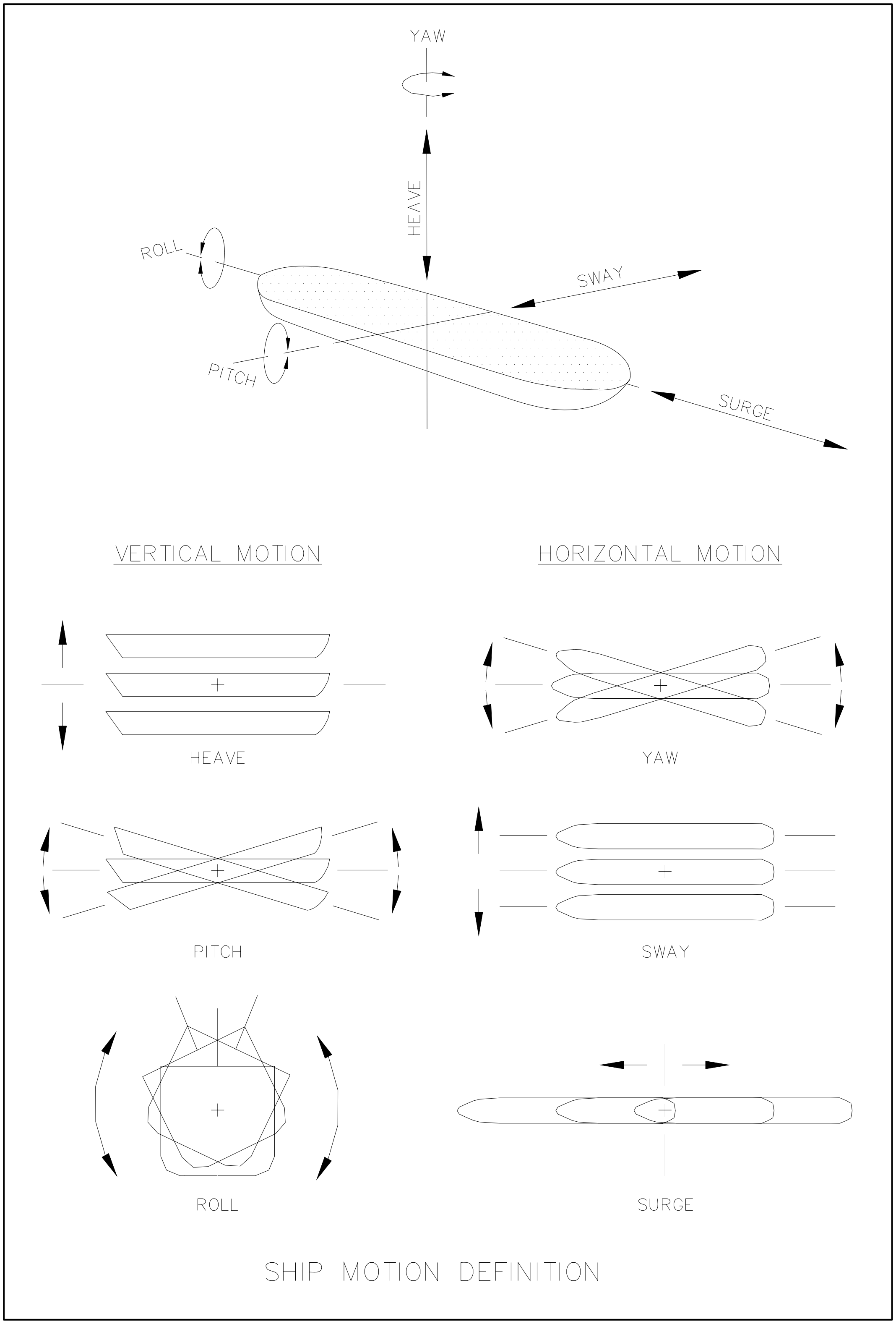

Figure 6-6. Ship wave motion definition

(5) Ship speed.

(6) Natural period of ship roll, pitch, and heave.

(7) Channel depth, ship draft, and underkeel clearance.

(8) Ebb or flood tide current condition.

(9) Channel overbank depth.

(10) Wave length and ship length and beam.

(11) Pilot strategy and response to waves.

(12) Wind speed and direction.

c. Waves.

(1) Waves are important to ship response in harbor fairways or entrance channels. Ocean waves are usually divided into two classes, depending on the period and origin of the waves. Seas are waves produced by local storms, while swell waves are propagated into the area of interest from distant storm systems. Ocean swell waves usually have longer periods than local seas, while wave heights of local seas may frequently exceed the heights of swell waves, particularly swell waves that have propagated over long distances. Observed wave heights are the combined heights of sea and swell, if both are present.

(2) Data on wave height, period, and direction are essential. These data and other offshore wave statistics are available for the U.S. coasts of the Atlantic and Pacific Oceans, the Gulf of Mexico, and the Great Lakes from the USACE Wave Information Study (WIS). These wave statistics are based on hindcasting waves from historical meteorological data as reported by Jensen (1983). The WIS data are contained in a series of published reports by McAneny (1995) and in a computer database maintained at the ERDC/WES. Wave data are available from the National Data Buoy Center (NDBC) for 3- and 12-m (10- and 40-ft) buoys as reported by Gilhouser (1983) and from the ERDC/WES Coastal and Hydraulics Laboratory (CHL) for nearshore pressure gage and small buoy data. When planning to collect local wave data as part of a project study, guidance is provided in EM 1110-2-1004, “Coastal Project Monitoring.” Advice and assistance in selecting equipment and siting equipment can be obtained from CHL.

(3) Deep-water wave data can be used to determine general trends in wave characteristics for the project area, but complexities in local bathymetry and shore orientation will produce a local wave climate that is different from the offshore data. The effects of the direction of water currents, ebb and flood tidal currents, on the waves must also be taken into account in determining the characteristics of the waves being encountered by the ship in an entrance channel. It is important that wave characteristics represent the waves that the ship will encounter since the motions of the ship (Figure 6-6) are the result of the ship’s response to the waves. The response of the ship is a function of the relative speed of the wave, the relative direction of the ship to the wave direction, the length of the wave to the ship’s length, the mass of the ship, and the ship type or hull form.

(4) Ignoring tidal current effects and irregular bathymetry, the local wave length for any depth of water can be approximated by Echart's (1952) equation for wave length:

$$\lambda = \frac{gT^2_{\ w}}{2\pi}\sqrt{\tanh\frac{4\pi^2 h}{T^2_{\ w} g}} \qquad (6\text{-}9)$$

where

λ = wave length

T_w = wave period

h = water depth

g = acceleration of gravity

Table 6-1 may be used to quickly approximate the wave length (λ_2) and maximum nonbreaking wave height (H_2) that is translated from deep water (λ_2 and H_o) into shallow water at an entrance, assuming idealized conditions of normal wave approach and straight and parallel depth contours with a nearshore slope of 1/100. Wave refraction is not included. Breaking wave heights (H_b) are controlled by wave steepness and water depth (h_b).

(5) More precise estimates of the nearshore wave climate can be obtained by using wave transformation procedures or math models with local bathymetry and offshore wave data. Some of these models are discussed in EM 1110-2-1414, "Water Levels and Wave Heights for Coastal Design," (paragraph 5-8a(8), Figure 5-54, and Table 5-5).

d. *Wave-Induced Ship Motion.* The vertical excursion of the ship bottom as a result of wave action is composed primarily of motions in the three response modes of heave, pitch, and roll (Figure 6-6). Because of response phase differences, the three vertical motion response modes may not necessarily be added together linearly. Pitch and heave are important when ships are transiting entrance channels with incident waves propagating along or near the channel axis. The ship will then respond to a head or following sea, with the wave crests being perpendicular to the predominant wave direction coming toward the ship bow or stern, respectively. Ship roll becomes important when waves are propagating in a direction perpendicular to the channel axis; this is called a beam wave.

e. *Ship Response to Waves.* Predicting ship response in harbor fairway for channel depth design is a major problem without easy solution. The seakeeping models used by naval architects are very difficult to apply and require a high level of specialized knowledge for useful interpretation and application. Physical models can be used to predict ship response from monochromatic waves, if model ships are properly scaled, constructed, balanced, instrumented, and tested. Spectral wave generators have been used (for example, at ERDC/WES to model statistically meaningful wave situations) to gain accurate ship response information for entrance channel design. Relatively few data have been collected for the variables of interest in determining ship response in waves, particularly for ship motions in relatively shallow-water conditions. This lack of data results in difficulty in verifying proposed models to predict the motion of a ship induced by waves and the extra depth required in entrance channels to compensate for this motion.

Table 6-1
Shallow Water Waves at Entrances (To convert feet to meters, multiply by 0.3048)

Period, sec	λ_o, feet	H_o, feet	λ_2, feet	H_2, feet	H_b, feet	h_b, feet
Depth at Entrance – 30 ft						
8	328	21	225	19.7	21	27
10	512	21	292	20.9	23.6	29.4
15	1152	17	453	19.7	24.7	29.7
20	2048	16.9	612	18	24.4	29
Depth at Entrance – 35 ft						
8	328	21	238	19.5	21	27
10	512	26	311	25.3	27.6	34.8
15	1152	20	487	22.5	27.9	33.7
20	2048	16.9	659	21.4	28.5	33.9
Depth at Entrance – 40 ft						
8	328	21	250	19.3	21	27
10	512	30	329	28.7	30.7	39.2
15	1152	24	518	26.2	32	38.8
20	2048	20.1	702	24.7	32.4	38.7
Depth at Entrance – 45 ft						
8	328	21	261	19.2	21	27
10	512	33	345	31.2	33	42.3
15	1152	29	547	31	36.8	45
20	2048	24.3	743	29.1	37.4	44.7
Depth at Entrance – 50 ft						
8	328	21	270	19.2	21	27
10	512	33	360	30.8	33	42.3
15	1152	33	574	34.6	40.6	49.8
20	2048	27.5	782	32.3	40.9	49.1
Depth at Entrance – 55 ft						
8	328	21	278	19.2	21	27
10	512	33	373	30.6	33	42.3
15	1152	37	599	38.1	44.2	54.7
20	2048	31.7	818	36.5	45.5	54.9

f. *Preliminary Design Guidance for Entrance Channel Depths.* For the purpose of preliminary design of entrance channel depths exposed to waves, several recommendations have been made. These are provided as follows:

(1) The Permanent International Association of Navigation Congresses (PIANC) sponsored an International Commission for the Reception of Large Ships (ICORELS) in 1974. Working Group IV reported these recommendations for determining the depth of channels (Netherlands Ship Model Basin 1980):

(a) Open Sea Area. When exposed to strong and long stern or quarter swells where speed may be high, the gross underkeel clearance should be about 20 percent of the maximum draft of the large ships being received.

(b) Waiting Area. When exposed to strong or long swells, the gross underkeel clearance should be about 15 percent of the draft.

(c) Channel. When sections are exposed to long swells, the gross underkeel clearance should be about 15 percent of the draft.

The gross underdeel clearance is by definition the minimum margin remaining between the keel of the ship and the nominal channel bed level when the ship moving at planned speed under the influence of the design wind and wave conditions.

(2) The International Association of Ports and Harbors (IAPH) also assembled a Committee on Large Ships (COLS), now the Committee on Port Safety, Environment, and Construction, which made these recommendations (Marine Board 1981). In the initial planning stages, the following generalizations may be valuable:

(a) Sections exposed to strong and long swell, gross underkeel clearance to be about 15 percent of the maximum drought.

(b) Sections less exposed to swell, gross underkeel clearance to be about 10 percent of the maximum drought.

(3) A more recent report by a joint PIANC-IAPH Working Group II-30 (PIANC) 1995) prepared in cooperation with the International Maritime Pilots Association (IMPA) and the International Association of Lighthouse Authorities (IALA) gives a more generous allowance for preliminary guidance for setting entrance channel depths. It suggests that values of 1.3 times the maximum ship draft or more may be used for preliminary design purposes.

g. Empirically Based Method for Estimating Vertical Ship Excursions in Waves. Exxon International Company published a report entitles “Underkeel Clearance in Ports” in 1982. Included in that report is a procedure to estimate the allowance required for a tanker due to wave-induced motions. Based on the model tests conducted at the Netherlands Ship Model Basin (NSMB) (Koele and Hooft 1969) and reported by PIANC (1975), the responses of a loaded, untrimmed 200K dwt tanker in shallow-water waves were estimated. The majority of the tests were conducted with ship speeds of 7 knots. Based on SOREAH model tests (1973a-c) and some theoretical predictions for a 21K dwt tanker performed by NSMB (1980), Kimon (1982) extrapolated the 200K dwt tanker responses and other vessel sizes. Vessel root mean squared (RMS) responses to 0.305-m (1-ft) waves are presented for a 200K dwt tanker in Figures 6-7 through 6-11 for relative wave headings of 0, 45, 90, 135, and 180 deg. Figures 6-12 and 6-13 provide information to adjust ship responses for different displacements, while Figures 6-14 and 6-15 provide allowances for wave encounters and periods. In general, the vertical motion is largest for the bow and beam waves. For a given direction, the response increases with wave period going from wind driven to swell type seas. Only relatively long waves, with periods greater than about 10 sec, have a significant effect on underkeel clearance. The response decreases with decreasing H/T ratio, i.e., shallower water, as the proximity of the bottom has a large damping effect as reported by Van Oortmerssen (1976). The effect of vessel speed is largely the result of its effect upon period of wave encounter. In head seas, the encounter period decreases with increased speed, whereas in following seas, the encounter period increases. Because of the shorter apparent wave period in head seas, the vertical motion response decreases. Conversely, in following seas, there is a longer apparent wave period and, thus, increased response. In beam seas, there is no appreciable variation with ship speed. Tanker size is most significant for quartering, head, and following seas, since the response in these seas is sensitive to ship length. In quartering seas, pitch has a much greater effect on vertical motions of smaller-size vessels.

An example of the computation of the underkeel clearance allowance for waves is provided. Assume a 270K dwt tanker that is loaded to a 21-m (68-ft) draft having a 52-m (170-ft) beam, a roll period of 10 sec and a pitch period of 10 sec operating at 5 knots in charted water depths of 17 meters (55 feet) and a tide level of 7 meters (22.9 ft). The channel length is 2 nm, and the sea state has an average wave height of 3 m (10 ft), a period of 15 sec, and a relative wave heading of 180 deg to the ship's motion. From Figure 6-11, the RMS response for a 200K dwt tanker in 0.3048-m (1-ft) seas is 0.296. The RMS response for a 200K dwt tanker at the given wave height is 0.296 times the significant wave height of 0.40 m (2.96 ft). The displacement response ratio from Figure 6-12 is 0.86, and the RMS response for the given ship is 2.96 times 0.86 or 0.77 m (2.55 ft). The period of encounter from Figure 6-15 is 17 sec. The number of wave encounters is estimated by the distance/speed over ground (2nm/5knts) times 3600/17 sec or 85. The wave encounter multiplier from Figure 6-14 is 4.25, and the wave allowance is 4.25 times (0.77 m (2.55 ft) or 3.3 m (10.85 ft).

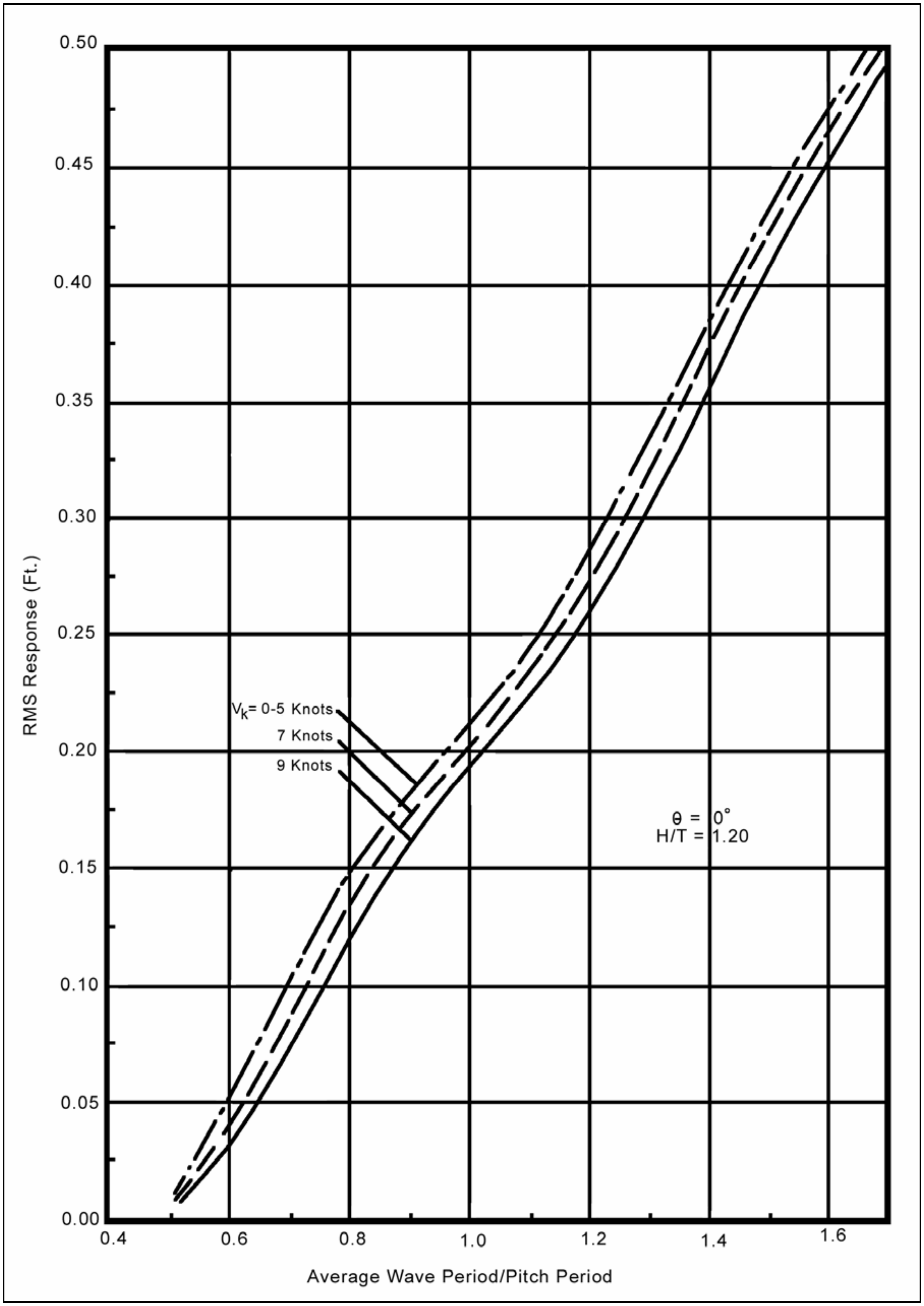

Figure 6-7. Head sea response, V_k = 0-9 knots

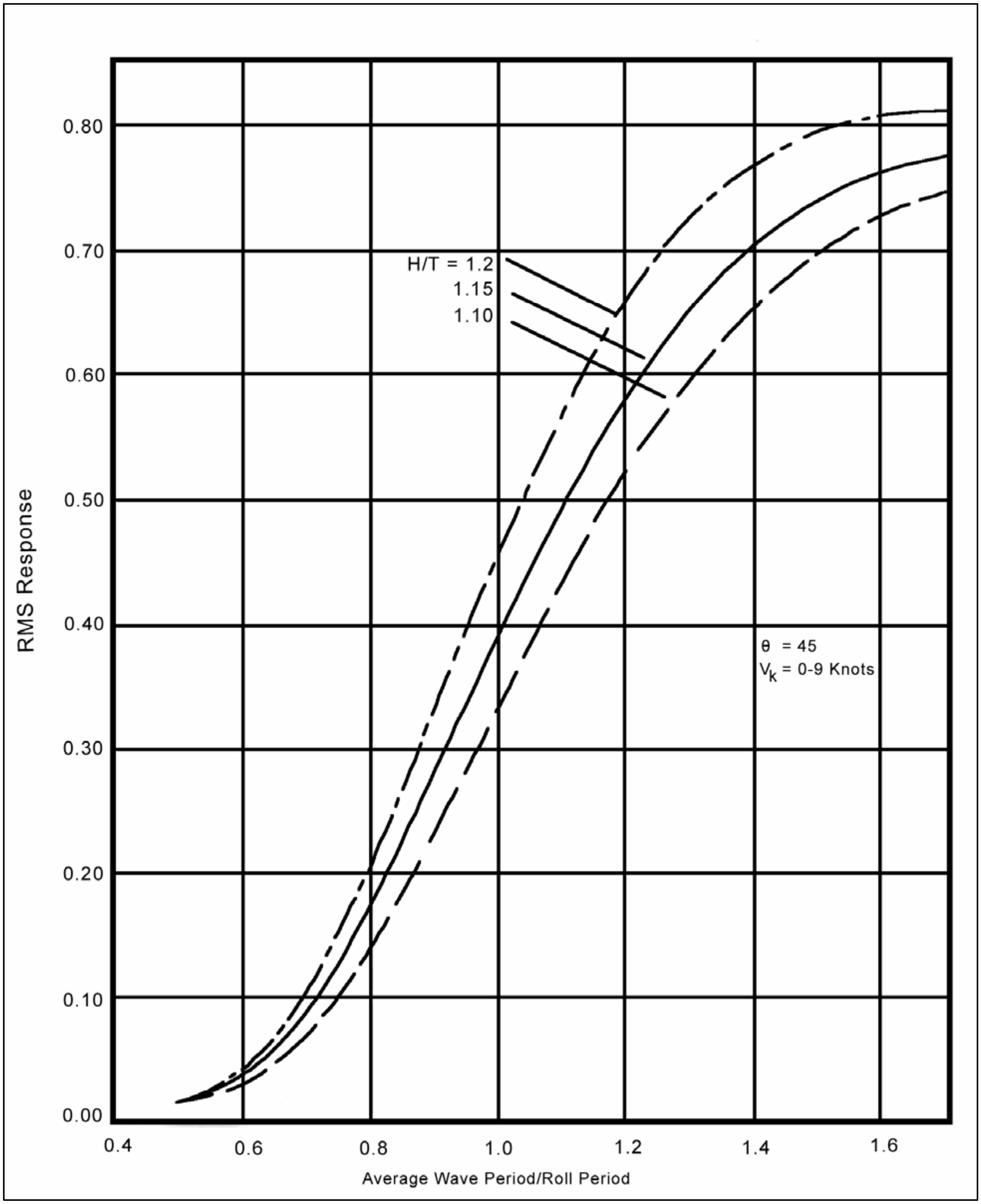

Figure 6-8. Bow sea response, V_k = 0-9 knots

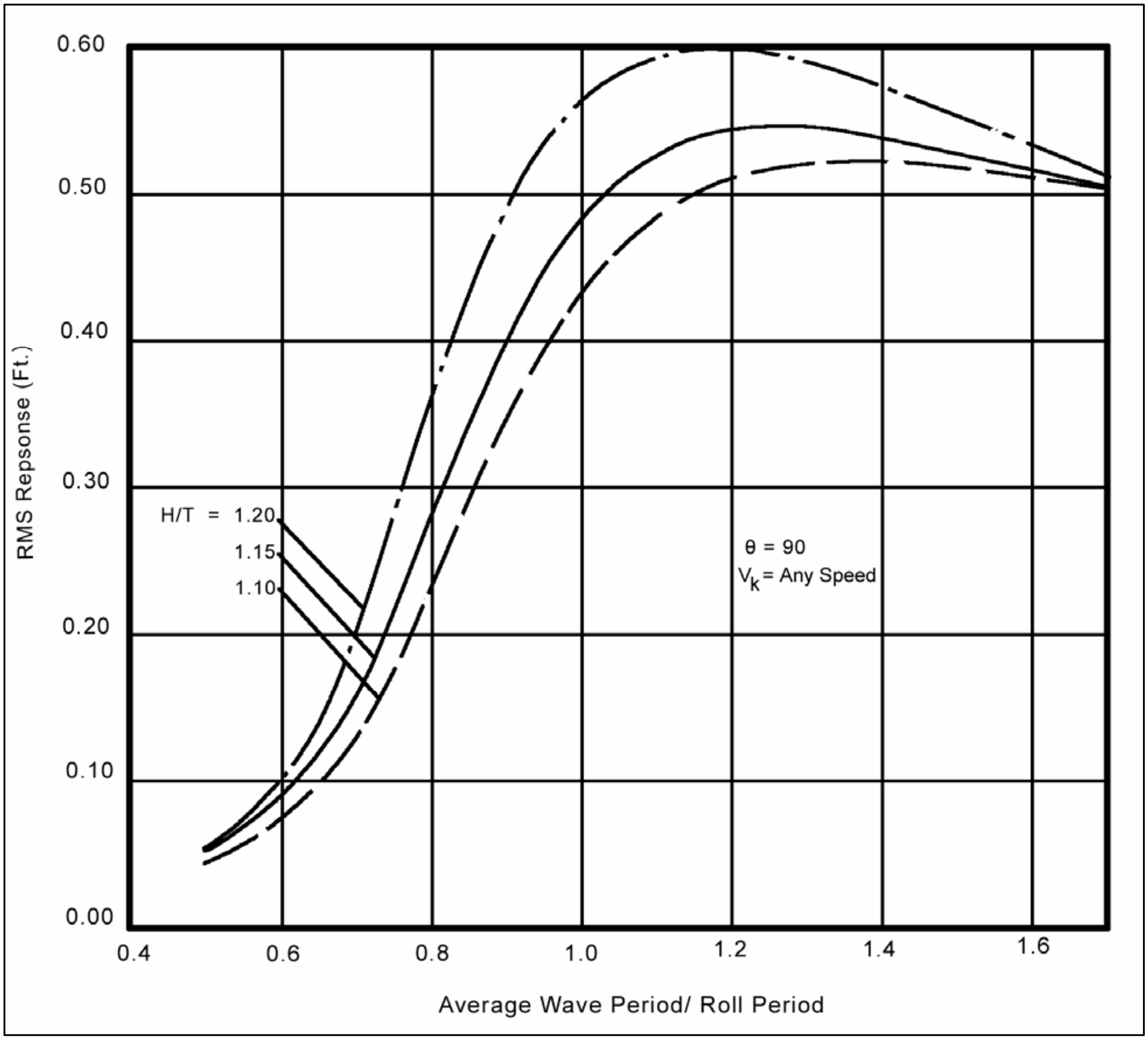

Figure 6-9. Beam sea response, V_k = any speed

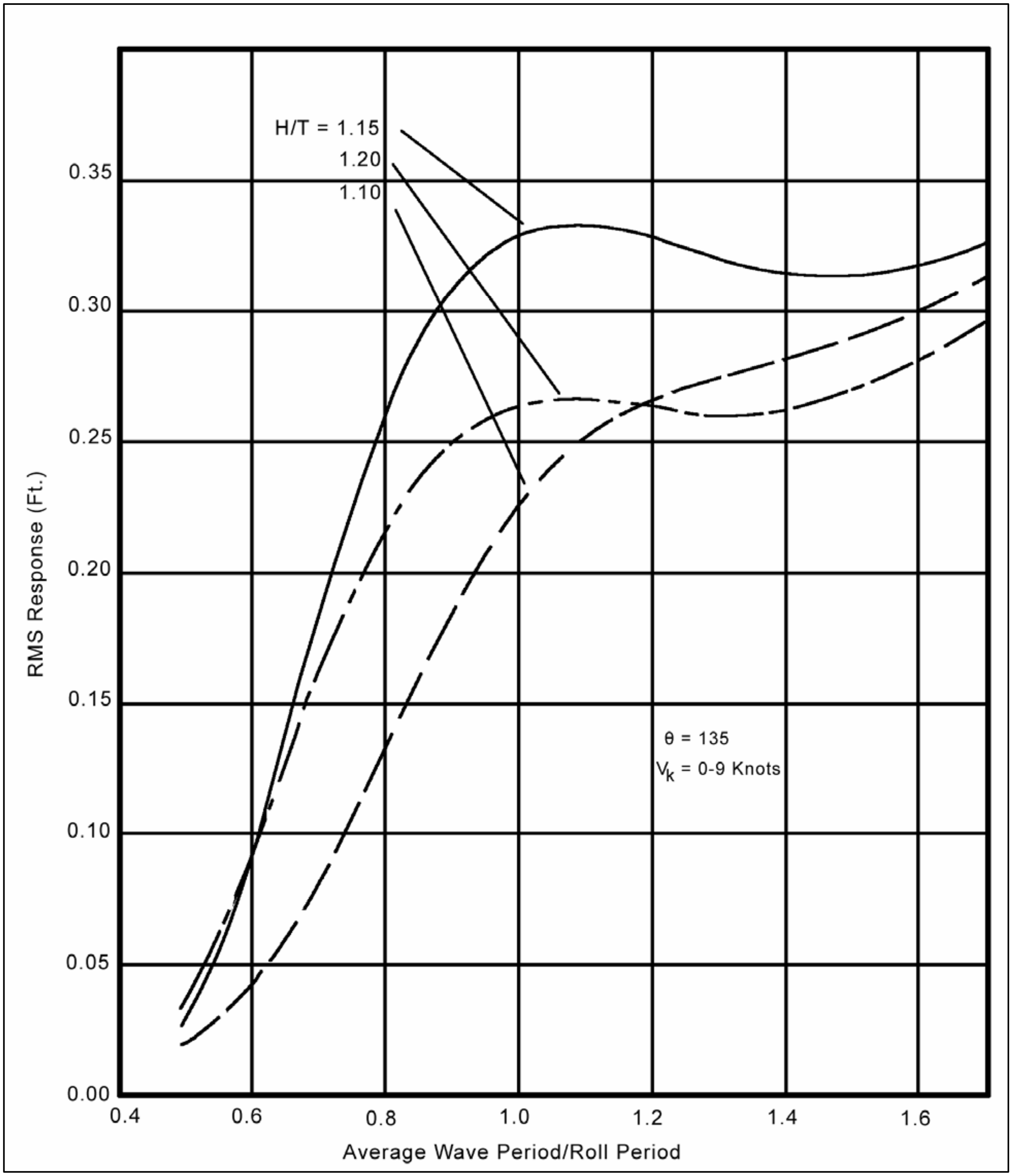

Figure 6-10. Quartering sea response, V_k = 0-9 knots

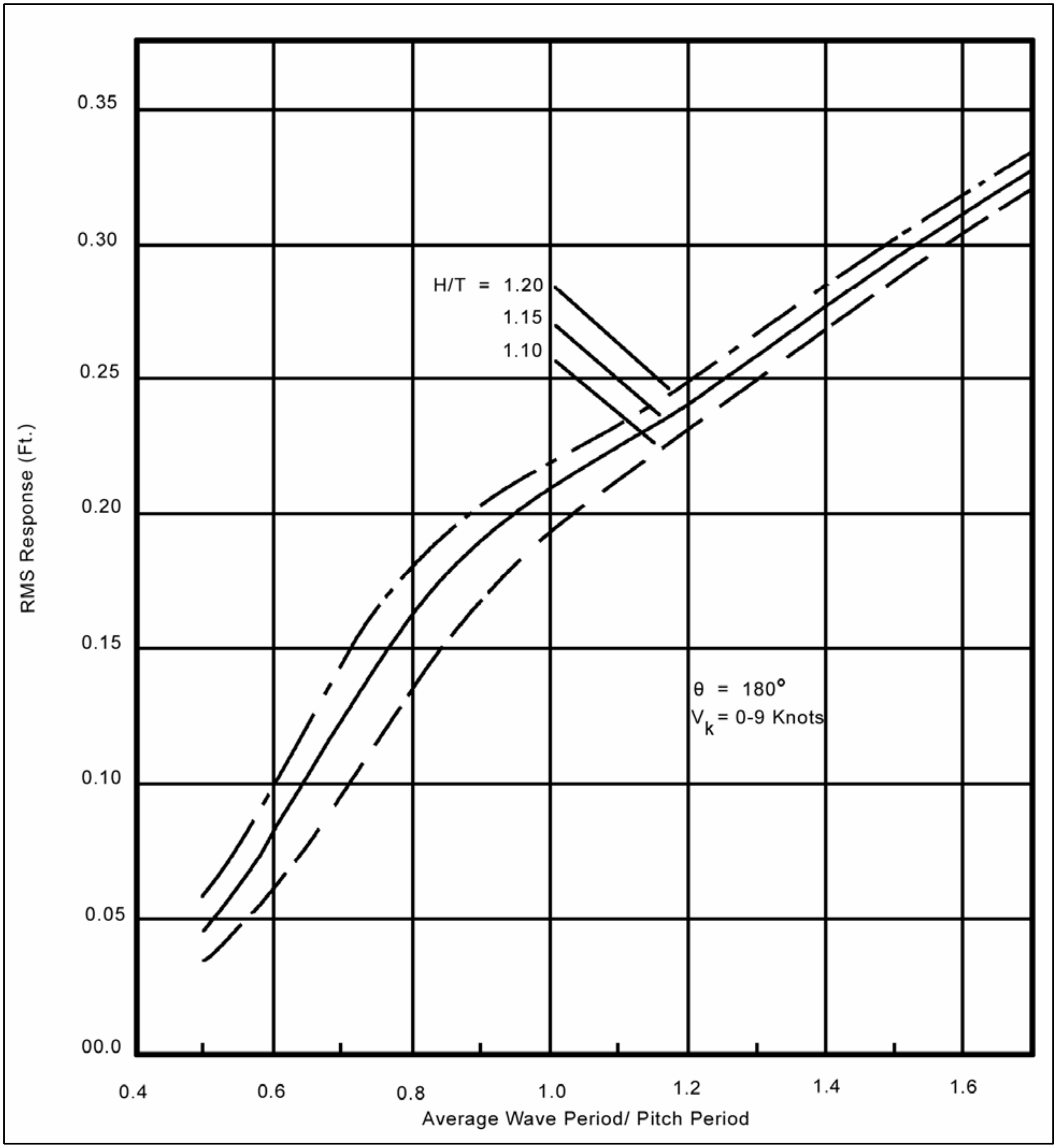

Figure 6-11. Following sea response, V_k = 0-9 knots

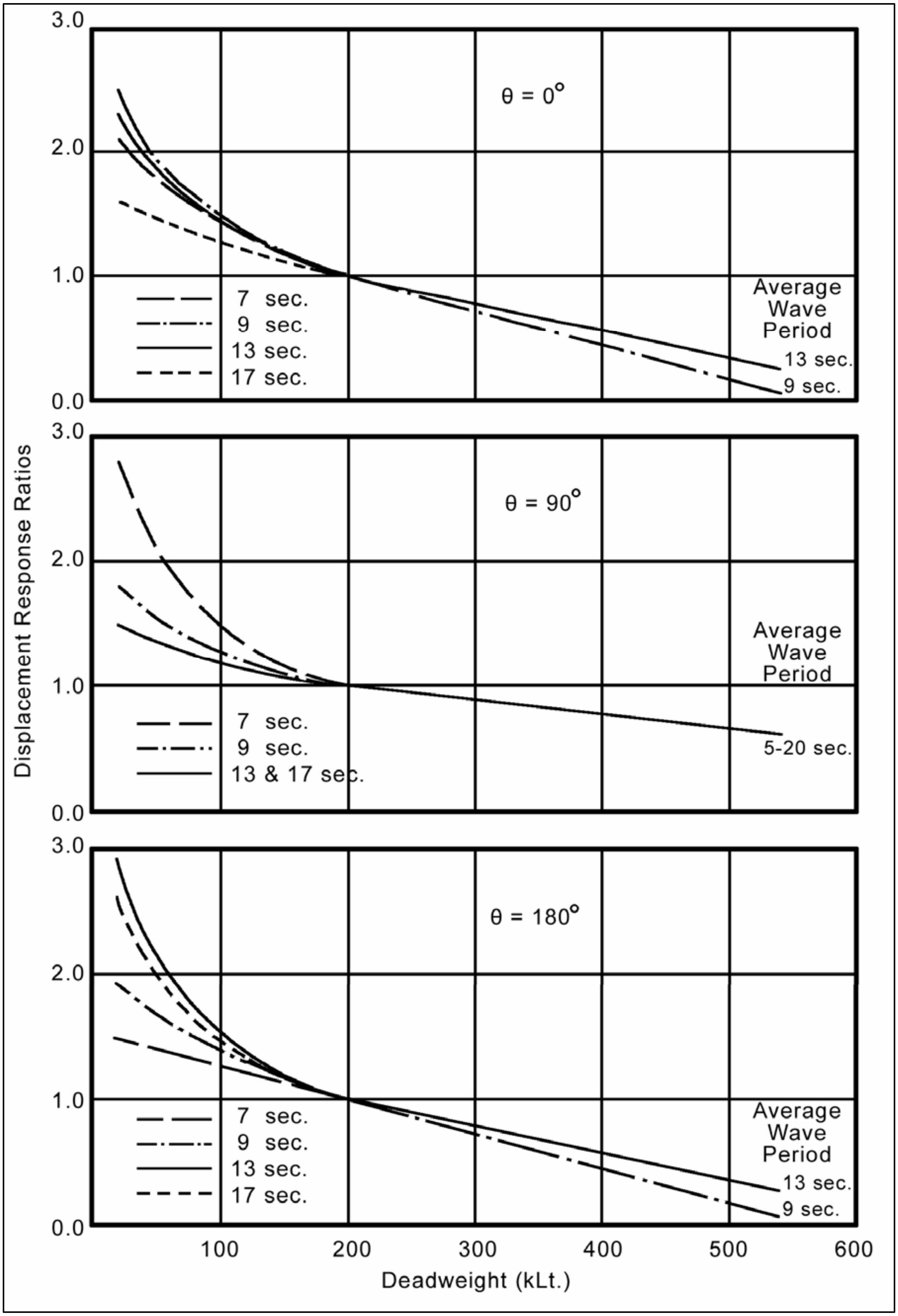

Figure 6-12. Displacement response ratios, θ = 0°, 90°, 180°

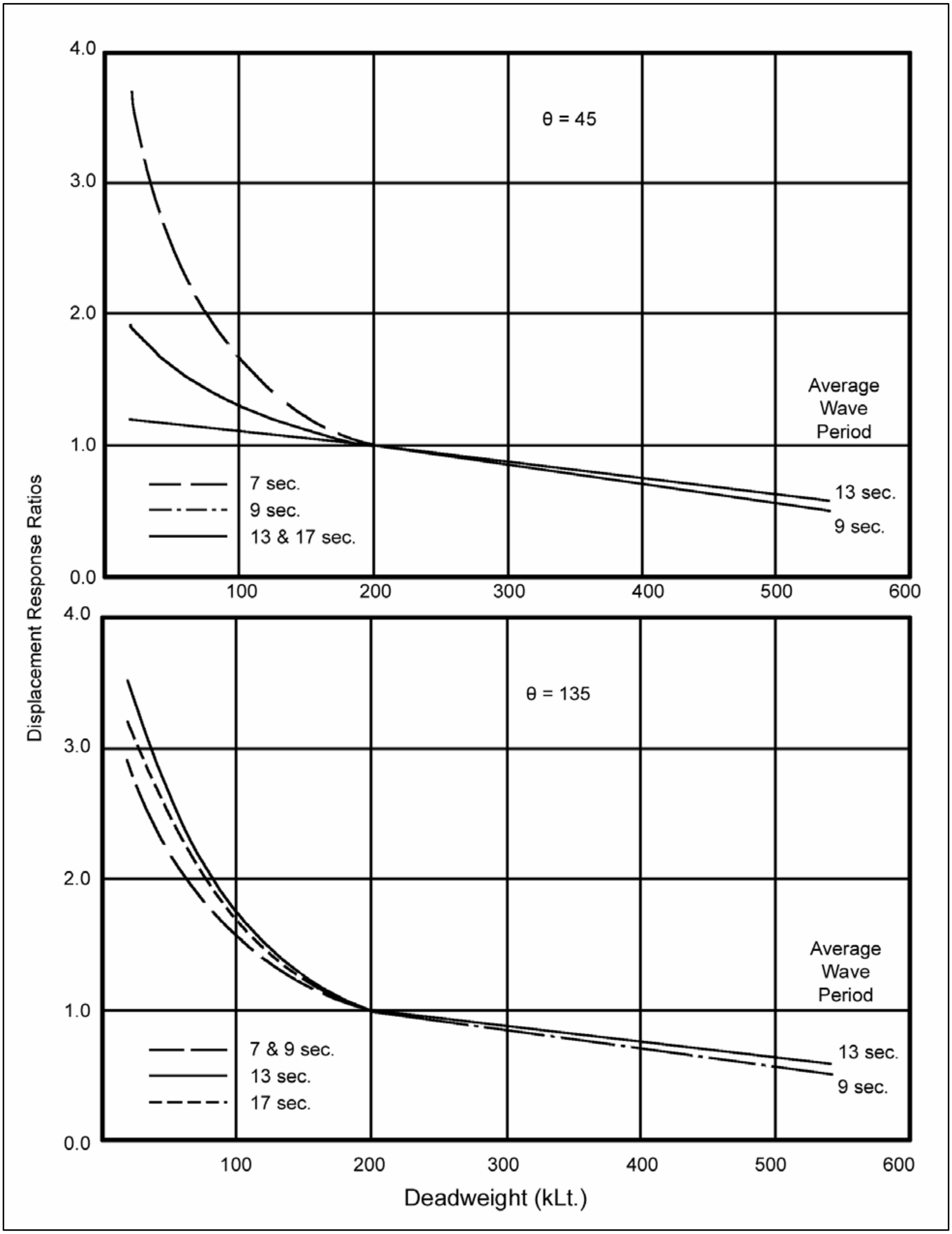

Figure 6-13. Displacement response ratios, θ = 45°, 135°

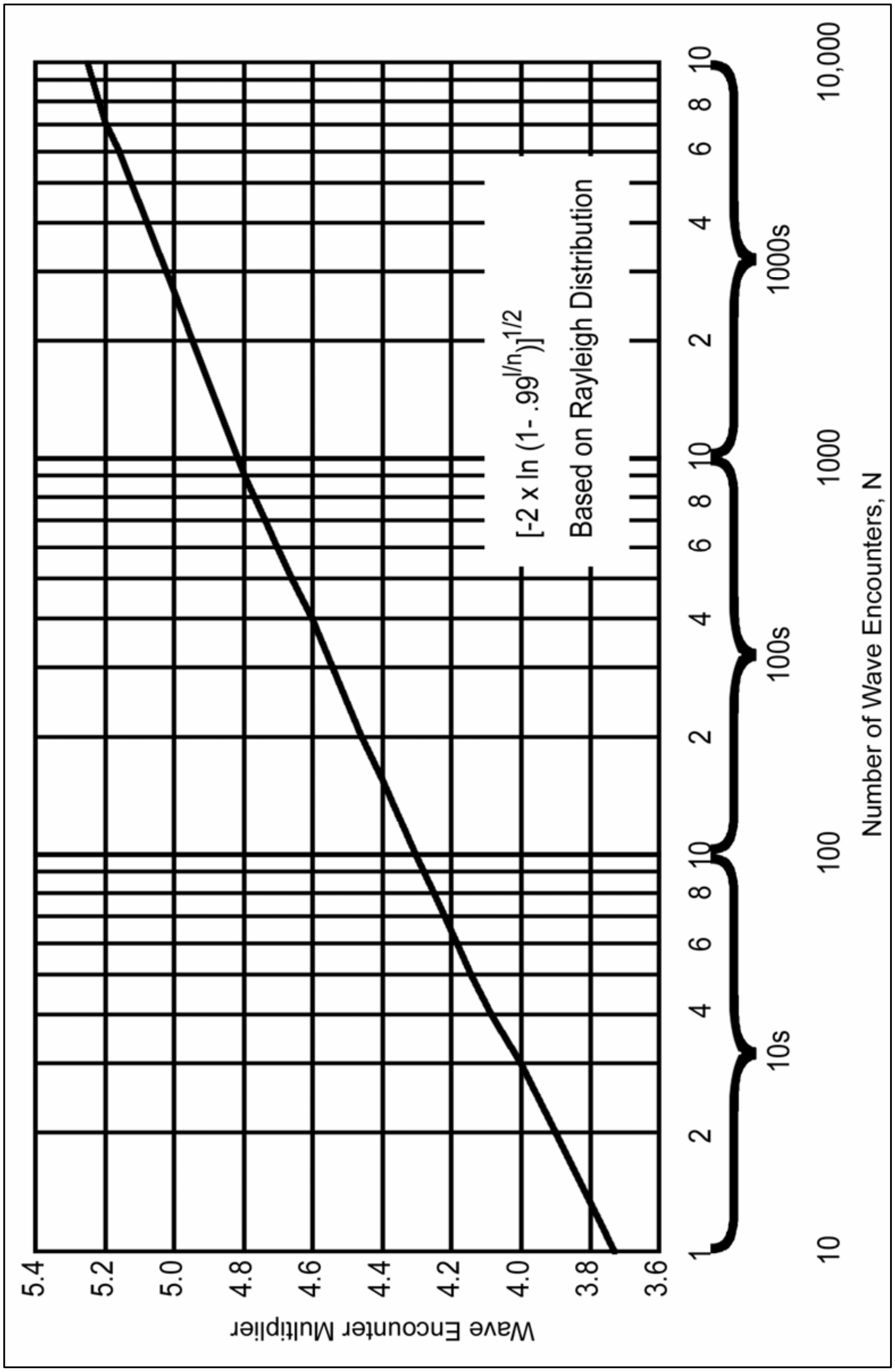

Figure 6-14. Wave encounter multiplier

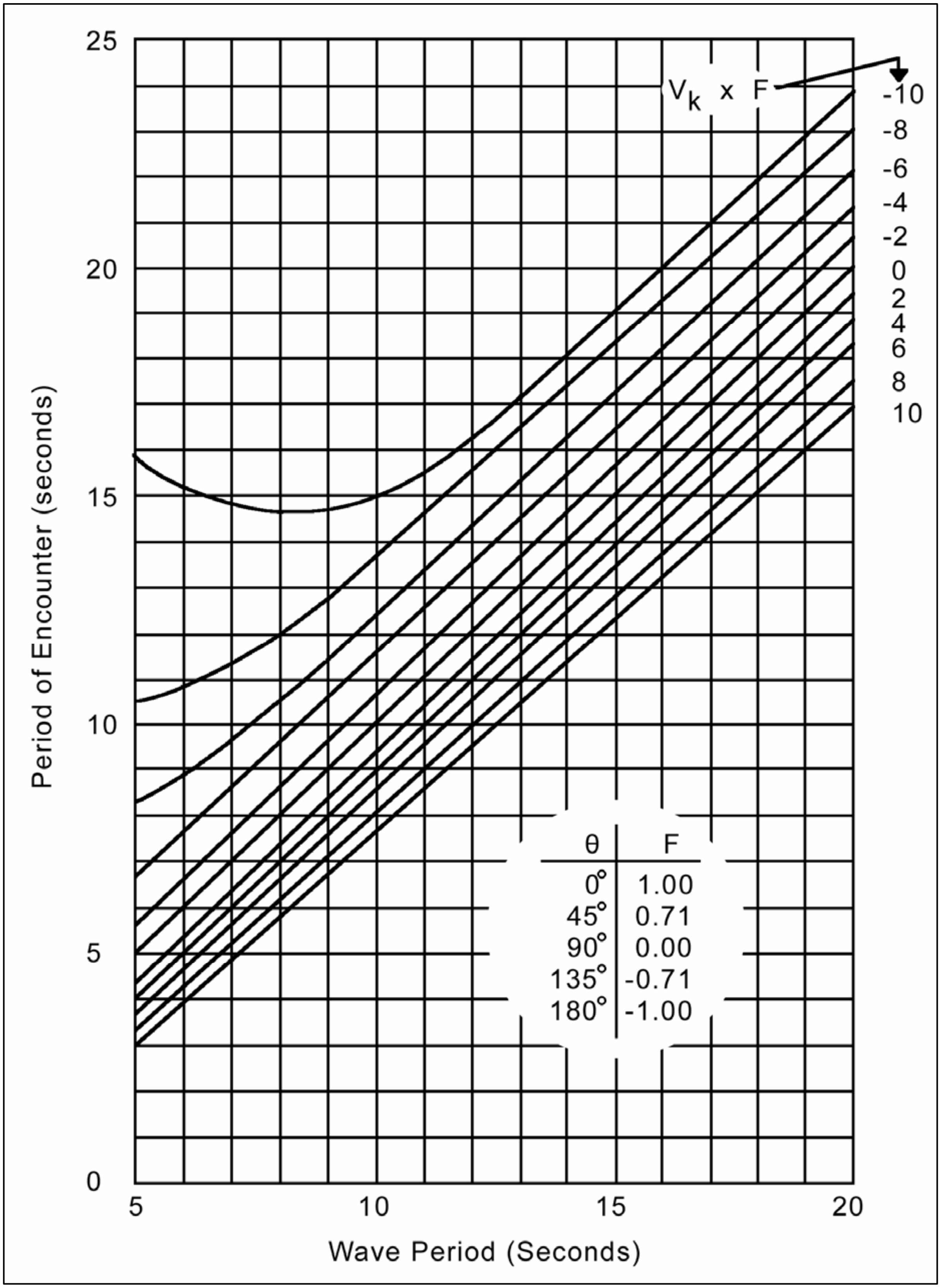

Figure 6-15. Wave encounter period

h. Columbia River Entrance Study. Ship response data were collected over a 2-year period at the mouth of the Columbia River, Washington/ Oregon (WA/OR), by the U.S. Army Engineer District, Portland (Wang et al. 1980). Because of the open nature of the entrance geometry, ship squat was considered negligible.

(1) Noble (1983) provides the summary of ship motions shown in Table 6-2. Myers (1969) indicates that the ship's natural period of roll is generally two or three times that of pitch. Table 6-2 indicates this is generally true of the degrees of roll and pitch as well.

Table 6-2
Summary of Heave, Roll, and Pitch Motions (after Noble 1983)

Σ% Freq Occ	Heav in ft Avg	Heav in ft Max	Roll Deg Avg	Roll Deg Max	Pitch Deg Avg	Pitch Deg Max
75	0.8	2.0	0.8	2.3	0.4	0.9
50	1.3	3.6	1.3	3.8	0.5	1.3
25	2.2	6.0	2.2	5.7	0.7	2.1
10	2.8	8.4	3.1	13.0	1.7	4.9
5	3.1	9.7	5.1	13.4	1.7	4.9
Max	4.1	12.4	5.5	17.5	2.2	6.0

Critical motions of a ship occur at the bow and stern and are most dependent on the wave height and encounter period. While wave height has the most influence on ship motion, the Columbia River study showed that the outbound voyages generally exhibited greater motions than inbound voyages. This demonstrates that shorter encounter periods cause greater bow/stern motions than longer periods. A relationship was derived using the independent variables wave height, natural pitch period, and encounter period of the ships to give the dependent variable of average bow or stern ship motion in waves for each voyage.

$$P_{avg} = 0.57 + 0.99\left(\frac{H_s T_\phi}{T_e}\right) \quad (6\text{-}10)$$

where

P_{avg} = average bow or stern ship motion in waves (meters (feet))

H_s = significant wave height (meters (feet))

T_ϕ = natural ship pitch period (seconds)

T_e = encounter period (seconds)

The relationship and the values used to develop it are found in Noble (1983). The 95 percent confidence limits are shown, and the relationship is reported to have a 0.86 correlation coefficient.

(2) The distribution of ship motions on an individual voyage follows the Rayleigh distribution. This distribution can be stated as:

$$P_{(p)} = 1.13 P_{avg} [-\ln(1-p)]^{1/2} \tag{6-11}$$

where

$P_{(p)}$ = bow or stern ship motion with a probability of 1-p of not being exceeded (meters (feet))

P_{avg} = average bow or stern ship motion during a transit (meters (feet))

p = probability of exceedence (percent)

If we assume that the critical ship motion for a particular transit should be $P_{(95)}$, then Equation 6-11 becomes:

$$P_{(95)} = 1.96 P_{avg} \tag{6-12}$$

By considering the frequency of occurrence of each wave condition, a distribution of the critical ship motion (critical ship motion being the $P_{(95)}$ or other selected $P_{(p)}$ of a transit under a particular set of conditions) is obtained for a particular ship (Figure 4, Noble 1983).

(3) Designers are most interested in extreme events. The ship response in wave data was reviewed, and the maximum ship motion for each of the outbound transits was plotted against the incident wave wave height. A linear regression was fitted through the maximum ship motion data and the 95 percent (two standard deviations) confidence limit added. The data and curves normalized by the wave height are shown in Figure 6-16. It is noted that use of Equations 6-10 and 6-11 result in nearly the same answers a the regression curve for the maximum ship motion. However, if it is desired to ensure that none of the ships will strike the bottom, then the recommended design curve should be used. Consultation with the bar pilots at the entrance will indicate the local practice.

i. Analysis Methods. For more accurate determination in final design, it is possible to investigate ship wave response in entrance channels using the following alternatives:

(1) Analytically, using strip theory or other theoretical calculation methods as developed by naval architects.

(2) Experimentally, using radio-controlled, free running, scaled ship models with wave response measurements.

(3) Direct, onboard ship measurements while transiting through the entrance channels.

Methods to conduct these types of investigations have been developed and are being used in entrance channel design on an experimental or research basis at present. However, further development of such techniques for entrance channel design is still being pursued, especially the analytical techniques.

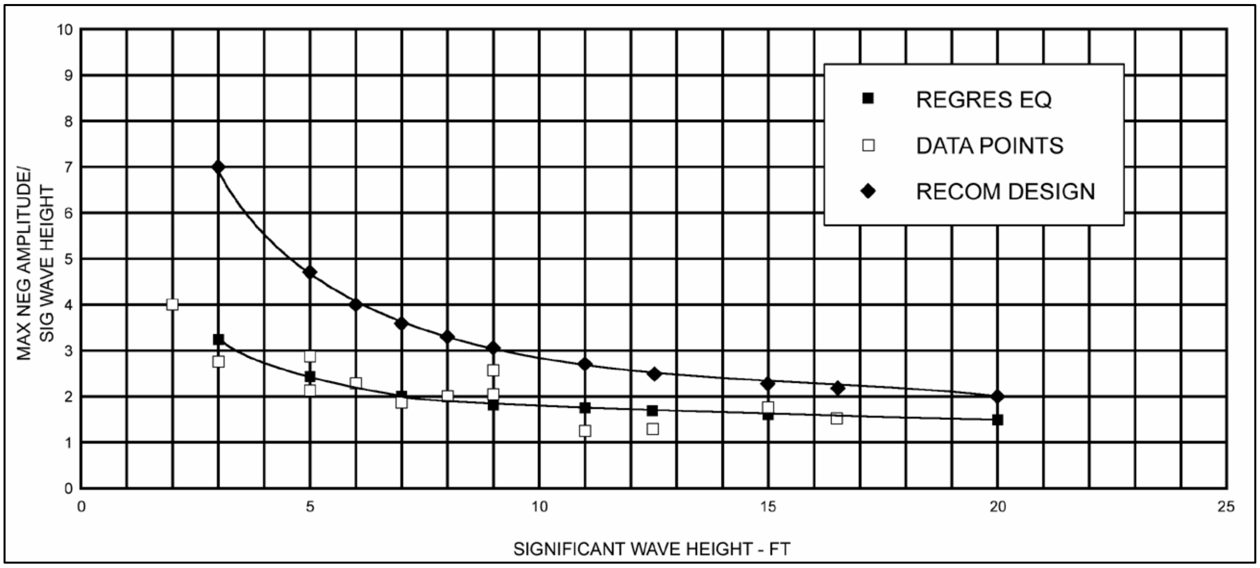

Figure 6-16. Maximum ship motion response, mouth of Columbia River - Outbound

j. *Alternative Approaches.* Some theories (Lewis 1989) are available and appear to be good for deep-water conditions. Naval architects use these computational methods for structural ship design for practical applications. However, use in shallow water for a typical entrance channel has not been demonstrated. A major factor affecting design includes operational considerations, e.g., when are ships brought into harbor and under what adverse conditions. Pilot strategy and response to wave conditions are also important, e.g., reducing speed generally will reduce ship response. Course changes can also modify the ship response; however, this is not usually possible in a dredged entrance channel. Ships will also sway or yaw in wave conditions, which can affect control of the ship, thus, all ship motions need to be calculated considering proper pilot control.

k. *Future Research.* Recently, ERDC/WES has been working with a research naval architecture company to develop and provide a ship motion response model to use on the ERDC/WES ship simulator. To date, results are encouraging; however, this effort is still considered a research tool and needs further verification.

Statistical approaches based on measured ship response functions to wave conditions have been developed and are being used by the U.S. Navy and the Ministry of Transport, The Netherlands. Research to develop a similar approach for U.S. ports is being proposed.

6-5. Depth Allowances

a. *Design Basis.* The designer must take care that the design channel depths developed from the economic analysis are at least equal to the loaded draft (summer, salt water) of the design ship, plus an allowance for the following factors:

(1) Ship squat.

(2) Ship lowering in fresh water.

(3) Vertical ship motion due to wave action.

(4) Safety clearance.

A diagram depicting these allowances and its relation to the channel bottom is shown in Figure 6-17.

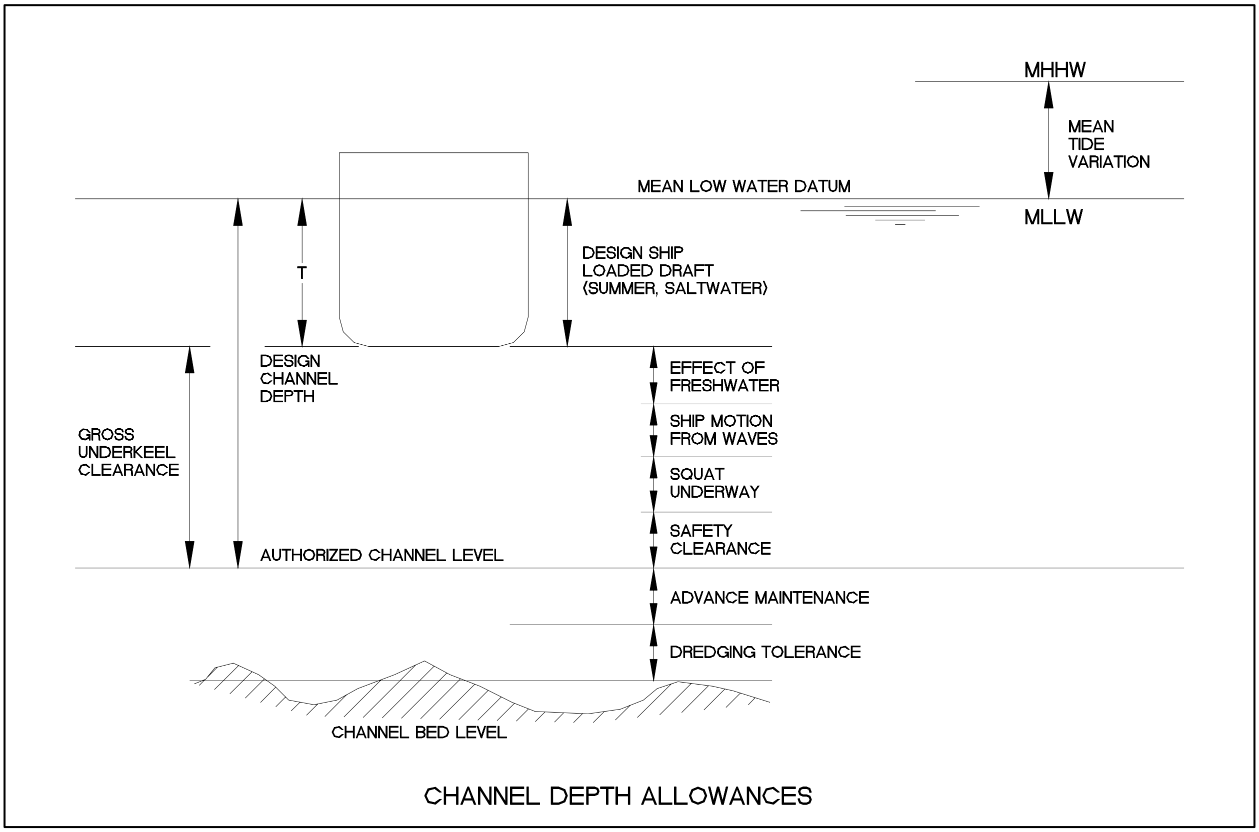

Figure 6-17. Channel depth allowances

b. *Effect of Fresh Water.* When ships call at ports with fresh or brackish water, the ship draft will increase because of a decrease in density of the water. The difference in unit weight between salt and fresh water is from 1025.84 kg/m^3 (64.043 lb/cu ft) to 998.98 kg/m^3 (62.366 lb/cu ft) or 26.86 kg/m^3 (1.68 lb/cu ft). Therefore, the ship draft will increase by 2.619 percent going from sea water to fresh water; brackish water at half the salinity would be 1.3095 percent. A ship with a 10.7-m (35-ft) draft would be increased in fresh water to 10.95 m (35.9165 ft) or about a 0.25-m (1-ft) increase. A maximum allowance of 0.25 m (1 ft) is appropriate in cases where the port is located in freshwater; 0.15 m (0.5 ft) is recommended when the port area is brackish.

c. *Trim.* In normal operations, most ships have capabilities to change the load and ballast conditions to provide desirable trim position. A ship in ballast (without any cargo) is loaded by pumping seawater into ballast tanks to provide sufficient draft to submerge the ship propeller and rudder. A small trim by the stern is usually beneficial for improved maneuverability and usually required by local pilots. Ships in motion will tend to change static trim conditions; tankers tend to trim down by the bow and containerships (and other fine-formed ships) trim down by the stern. The provision of a channel depth allowance for ship trim conditions is usually not necessary, since this is an operational decision to be determined by the local pilots as reflected by local port needs and requirements.

d. *Shallow-Water Effects.* Channel design bottom clearance should consider safety and efficiency of ship traffic in project operation. Small underkeel clearance will affect ship squat, maneuverability, and resistance compared to normal deep-water ocean operations. Pilots report that ships become more difficult to handle at small underkeel clearances, requiring large rudder angles to steer and turn ships in curves. Ships sailing in shallow water call for increased engine speed and power, which has an impact on fuel consumption. The potential for bank failure, bottom material movement, and scour increases considerably as power is augmented to the propeller to maintain desired ship speed.

e. *Safety Clearance.* In the interest of safety, a clearance of at least 2 ft (0.6 m) is normally provided between the bottom of a ship and the design channel bottom to avoid damage to ship hull, propellers, and rudders from bottom irregularities and debris. When the bottom of the channel is hard, consisting of rock, consolidated sand, or clay, the clearance should be increased to at least 0.9 m (3 ft).

f. *Advance Maintenance.* Advance maintenance consists of dredging deeper than the channel design depth to provide for the accumulation and storage of sediment. Justification for advance maintenance is based on depth reliability and economy of less frequent dredging. Economic consideration should also be given to providing a sediment trap near a project entrance channel as an alternative to advance maintenance. Deeper channels will tend to be more efficient sediment traps and can shoal at faster rates (Trawle 1981). However, a deeper channel might tend to localize shoaling and could reduce the length of channel to be dredged and cost of maintenance dredging. Estimates are needed on several depth increments of advance maintenance and expected effect on shoaling rates to determine the optimum depth. Conditions will vary with each project, and the design depth and overdredging that might be applicable for advance maintenance should be based on an evaluation of local conditions at each project. Generally, depth increments of 0.6 or 0.9 m (2 or 3 ft) are normal advance maintenance allowances.

g. *Dredging Tolerance.* In addition to advance maintenance dredging, an additional 0.3 to 0.9 m (1 to 3 ft) below the selected dredging depth is generally provided as a dredging pay item because of the inability to dredge at a uniform depth with fluctuating water surface. This additional dredging allowance is referred to as dredging tolerance. Depth allowances for advance maintenance and dredging tolerance are provided in addition to the design (authorized) depth.

h. *Total Depth.* The design (authorized) depth will include the various allowances as shown in Figure 6-17. Advance maintenance and dredging tolerance are provided in addition to the design depth.