(3) The added length is given by (Sorensen 1986, adopted from Miles (1948))

$$\ell'_c = \frac{-W}{\pi} \ln \left(\frac{\pi W}{\sqrt{g d_c}\ T_H} \right) \qquad \text{(II-7-19)}$$

where

W = channel width

d_c = channel depth

II-7-6. Flushing/Circulation

a. Statement of importance.

(1) An important aspect of harbor design is the water circulation that occurs within the harbor and between the harbor and the surrounding water body. Water exchange with the surrounding water body will produce a flushing action in the harbor. Flushing is important to reduce the level of chemical, biological, and floating solids pollution in the harbor. Typically, a criterion such as the exchange of X percent of the water in the harbor within a certain time period or, alternatively, exchange of Y percent of the water in the harbor each tidal cycle might be set as a design goal.

(2) Circulation patterns within a harbor should eliminate areas of stagnant water where pollution levels will rise and fine sediment deposition may occur. This can occur, for example, in closed-end channels such as pier slips and residential canals. Strong circulation is desired as long as adverse high-velocity currents are not generated.

(3) Natural harbor circulation and flushing should be optimized. This can be accomplished by:

(a) Siting the harbor to make use of ambient currents that will pass the harbor entrance.

(b) Considering water circulation when determining the number, size, and placement of harbor entrances.

(c) Establishing the harbor planform and internal structure locations so that circulation is optimized and potential pollution sources are located in areas of strong water circulation.

(d) Employing (where incident wave action allows) harbor protective structures such as floating breakwaters and vertical barriers with bottom openings that permit flow into and out of the harbor.

(e) Installing culvert pipes through more massive harbor protective structures. This natural flushing can be supplemented by installing pumping systems that bring exterior water into dead areas of the harbor or remove polluted water from these areas.

b. Flushing/circulation processes.

(1) Tidal action.

(a) As the tide rises, ambient water will enter a harbor and mix with the water in the harbor. On the subsequent falling tide, a portion of this ambient/harbor mixture will leave the harbor. The net result is the exchange of some harbor water with water from outside the harbor. The efficiency of this exchange depends primarily on two factors. One factor is the ratio of the volume of water that enters on one tidal cycle (the tidal prism) to the total volume of water in the harbor. This ratio, in turn, will depend on the tide range, the hydraulic efficiency of the harbor entrance, and the water depths in the harbor. Generally, the larger the value of this ratio, the more exchange that will occur. The other factor is the momentum of the incoming jet of water on the rising tide, and the consequent amount of penetration of this jet and its resulting angular momentum as it establishes a rotating gyre inside the harbor. The strength of this jet is related to the amount of flushing that will occur and the strength of the tidally induced circulation in the harbor.

(b) The most commonly used factor for defining the effectiveness of tidally induced harbor flushing is the average per cycle exchange coefficient *E* (Nece and Richey 1975) given by

$$E = 1 - \left(\frac{C_i}{C_o} \right)^{\frac{1}{i}} \tag{II-7-20}$$

where C_o is the initial concentration of some substance in the harbor water and C_i is the concentration of this substance after *i* tidal cycles. *E* may be defined at a point in the harbor by using concentration values at that point or may be defined for the entire harbor by using spatially average concentration values for the entire harbor. *E* is the fraction of harbor water removed each tidal cycle. Equation II-7-20 assumes essentially repetitive identical tides and no further addition of the marker substance to the harbor.

(c) As an example of the use of the exchange coefficient, consider Figure II-7-39, which is modified from Falconer (1980) and based on physical and numerical model results. Figure II-7-39 shows the spatial average exchange coefficient for a rectangular harbor having the dimensions L and B shown in the insert. Note where the harbor entrance is located. *E* has a peak value of about 0.5 when *L*/*B* is near unity (i.e. a square harbor). For *L*/*B* values outside the range of 0.3 to 3, the flushing of the harbor is much less effective. The tidal prism ratio (*TPR*), defined as the tidal prism divided by the total harbor volume at high tide, was 0.4 for the results shown in Figure II-7-39.

(d) Another factor used to define the amount of flushing is the "flushing efficiency," defined as the exchange coefficient divided by the tidal prism ratio (i.e. *E*/*TPR*) expressed as a percentage (Nece, Falconer, and Tsutumi 1976). Flushing efficiency compares the actual water exchange in one cycle with the volume of exchange that would occur if the incoming tidal prism completely mixed with the harbor water on each cycle. Table II-7-3 shows some results for five small-boat harbors in the state of Washington. These results are based on model tests (Nece, Smith, and Richey 1980).

(e) Note that the exchange coefficients are all around 0.2, which is below the value for the more idealized rectangular harbors (Figure II-7-39). And, for relatively consistent exchange coefficients, the flushing efficiency showed a much greater range of values. For the rectangular harbor in Figure II-7-39 where the TPR is 0.4, the flushing efficiency would vary from 0 up to about 125 percent. The desirable exchange coefficient or flushing efficiency for a given harbor would depend on the level of pollution in the harbor versus the desired harbor water quality. Although higher exchange coefficients and flushing efficiencies generally indicate better harbor flushing by tidal action, there may still be small pockets of stagnant water in a generally well-flushed harbor.

(2) Wind effects.

(a) Wind acting on the water surface will generate a surface current that, in water depths typically found in harbors, will essentially be in the direction of the wind. Owing to Coriolis effects, the current will be a few degrees to the right of the wind in the Northern Hemisphere; e.g., see Neumann and Pierson (1966) or Bowden (1983). If the distance over which the wind blows and the wind duration are sufficient, the surface

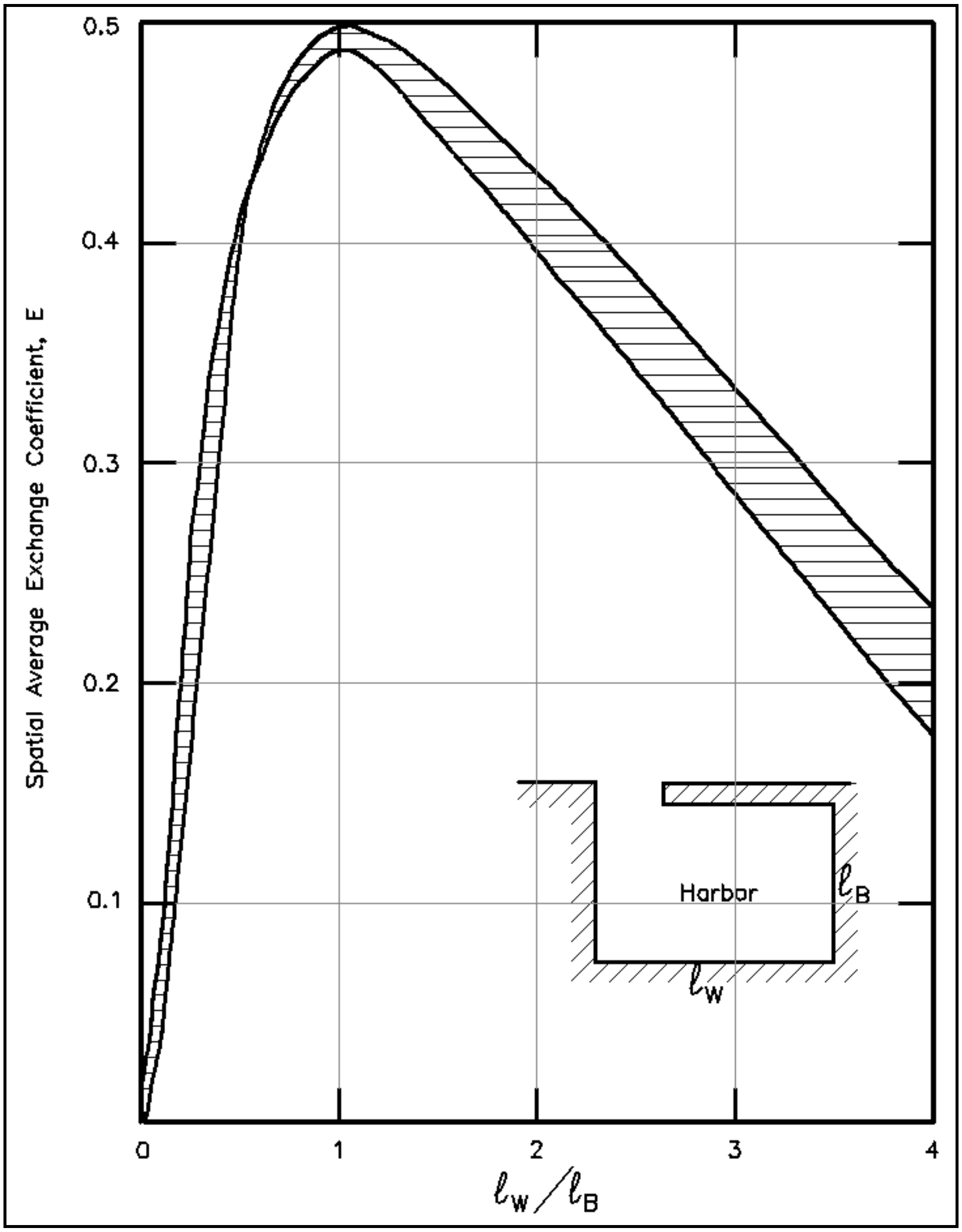

Figure II-7-39. Exchange coefficients - rectangular harbor, TRP = 0.4 (modified from Falconer (1980))

Table II-7-3
Flushing Characteristics of Small-Boat Harbors

Harbor	Tide Range (m)	Exchange Coefficient	Flushing Efficiency (%)
Des Moines	1.07	0.22	123
Edmonds	0.82	0.14	100
Lagoon Point	0.91	0.16	63
Penn Cove	1.22	0.19	75
Lake Crockett	1.83	0.22	78

current will approach a velocity equal to 2 to 3 percent of the wind speed. But, given the lengths of open water found in most harbors, it is likely that the resulting current velocity will be less than this magnitude.

(b) The wind-induced surface current would cause a lateral or bottom return flow to develop, resulting in some circulation in a harbor under sustained winds. The resulting current pattern would be very dependent on the wind direction and the harbor geometry. Some flow in or out of the harbor entrance could develop. Also, the surface current will skim floating materials to the down-wind areas of the harbor. Generally, wind-induced circulation and flushing will be much less effective than circulation and flushing induced by tidal action.

(3) River discharge.

(a) Fresh water may enter a harbor from the land side as surface runoff or as concentrated flow in rivers that enter the harbor. Surface runoff will generally contribute more to the harbor pollution load because of the agricultural or urban pollutants in the water than it will to alleviating pollution by contributing to harbor flushing.

(b) Likewise, the efficacy of river discharge in easing harbor pollution will depend on the quality of the river water. If there are lower chemical and biological pollution loads in the river water than in the harbor, the flushing effect will be positive. But this could be counterbalanced if the river has a suspended silt load that will deposit in the slower moving harbor water. Silt suspension is a particular problem inside sections of the harbor such as pier slips. The silt-laden water may set up a turbidity current that will force bottom water having higher silt concentrations into a dead area, where it then deposits (Lin, Lott, and Mehta 1986). The silt load in a river may be relatively low during periods of normal river flow, but the concentration of suspended sediment may increase by orders of magnitude during storms.

(c) Some harbors are built inland from the coast along river/estuary systems. River flow past the harbor entrance can have conflicting effects. The flow past the entrance can generate a rotary flow system at the entrance that produces some flushing of the harbor. But, if the river silt load is significant, there can be a net deposition of sediment in the harbor near the entrance.

c. Predicting of flushing/circulation. Harbor flushing rates and circulation patterns can be predicted by numerical and physical models and by field studies. Often, some combination of these efforts is the most effective approach. Numerical and physical models benefit from the collection of field data that is usually required to calibrate and verify the models.

(1) Numerical models.

(a) A numerical model of the hydrodynamics of a harbor can be developed by employing finite difference solutions of the equation of mass balance and the two horizontal component momentum equations. With the appropriate boundary conditions at the fixed boundaries of the harbor and the tide as a forcing function at the harbor entrance, one can compute the time-dependent water flow velocities and water surface elevations at selected grid points in the harbor. If so desired, the surface wind stress on the water can also be employed as a forcing function. And river flow into the harbor can be specified at points along the harbor boundary. From the computed time-dependent grid of flow velocities, the resulting circulation patterns in the harbor can be defined.

(b) Commonly, the two-dimensional depth-integrated forms of the equations are used. That is, the horizontal flow velocities are averaged over the water depth and it is assumed that the water column is well mixed so there is no vertical density stratification. Also, it is assumed that vertical flow accelerations are small compared to the acceleration of gravity, so the pressure is hydrostatic and vertical components of flow velocity may be ignored. This latter limitation would require that there be no abrupt significant depth changes in the harbor. These equations are known as the long-wave equations (see Part II-5). Harris and Bodine (1977) present a derivation of these equations and discuss their formulation for numerical solution.

(c) If the solute advection-diffusion equation is added to the numerical hydrodynamic model, the movement and distribution of pollutants in the harbor can be computed. From this, the harbor exchange coefficients and flushing efficiency can be determined. An interesting application of numerical modeling to investigate harbor circulation, flushing, and variations in dissolved oxygen has been carried out by the Waterways Experiment Station for Los Angeles and Long Beach Harbor in California (Vemulakonda, Chou, and Hall 1991). Typical two-dimensional and a quasi-three-dimensional numerical model investigations studied the impact of deepening channels and constructing landfills in the harbor.

(d) Chiang and Lee (1982), Spaulding (1984), and Falconer (1980, 1984, 1985) provide other examples of applying the long-wave equations to calculate harbor hydrodynamics and adding the solute transport equation to determine the flushing characteristics of harbors.

(e) These numerical models have a number of advantages - they are flexible in that it is easy to adjust input tide and wind conditions as well as harbor bottom and lateral boundary conditions, and they do not have some of the scale/distortion problems found in physical models. But they also have disadvantages - they are a two-dimensional representation of the flow field in the harbor, and since calculations are done for a grid, flow details that are smaller than the grid dimension are not represented. This latter disadvantage makes it difficult to investigate, for example, the eddies generated by flow separation at the harbor entrance or at internal structures. It can be overcome to some extent by decreasing the grid point spacing in key segments of the harbor such as around the harbor entrance (Falconer and Mardapitta-Hadjipandeli 1986).

(f) Numerical models require that a number of empirical coefficients (e.g. surface wind stress and bottom stress, eddy viscosity, and component diffusion coefficients) be defined in order to run the model. Thus, confidence in the model can be significantly increased if field data are available to calibrate the model and verify subsequent model results.

(2) Physical model studies.

(a) Physical model studies have been conducted to investigate flushing and circulation patterns for existing and proposed harbors (Nece and Richey 1972, Schluchter and Slotta 1978, Nece 1985, Nece and Layton 1989) and for basic planform patterns of idealized harbors (Nece, Falconer, and Tsutumi 1976; Jiang and Falconer 1985).

(b) Physical models of harbors are designed to investigate tidal flushing, so they are based on Froude similitude (Hudson et al. 1979). They typically have a distorted scale, with the vertical scale being larger than the horizontal scale. Common model scale ratios that have been used are 1:30 to 1:50 for the vertical scale and 1:300 to 1:500 for the horizontal scale. It is assumed that wind effects are negligible and that the water column has no density stratification. Also, the effects of Coriolis acceleration are not modeled. Most harbors are sufficiently small that Coriolis effects can be neglected.

(c) For models using water and having the typical harbor model/prototype scale ratios, Froude and Reynolds similitude are incompatible. Consequently, model Reynolds numbers are underscaled. Thus, inertial effects are scaled but turbulent diffusion is not scaled. To minimize these effects, some experimenters have installed roughness strips at the model harbor entrance to generate turbulence. Thus, local diffusion-dispersion of solutes is not accurately replicated but advective transport of solutes is replicated. The latter typically dominates. Fine details of the internal flow circulation are not replicated, but gross circulation patterns are.

(d) Circulation patterns are typically measured by photographing the movement of floats. Model exchange coefficients and flushing efficiencies are measured by adding dye to the water at the start of tests and then measuring the decrease of the dye concentration during subsequent tidal cycles. While exchange coefficient values from the model and model circulation patterns do not precisely equate to prototype conditions, these harbor model studies can provide a basis for comparing alternative design features for a proposed harbor or guidance in modifying an existing harbor.

(e) Table II-7-4 lists, for ease of comparison, the relative advantages of physical and numerical models for harbor flushing and circulation studies. The table gives a general comparison, but for a specific application, modelling experts should be consulted before deciding whether to use a numerical or physical model or some combination of both.

Table II-7-4
Advantages of Physical and Numerical Models

Physical Models
Provide good visual demonstration of flow patterns
Some three-dimensional effects can be represented relatively easily
Intricate harbor boundaries can be easily simulated
Numerical Models
Wind stress and Coriolis effects can be simulated
Lower model development and maintenance costs
Easy to store model for future use
Easy to adjust or expand model boundary conditions
Extensive output data can easily be obtained

(3) Field studies.

(a) Limited field studies at an existing harbor may be conducted to obtain sufficient data to calibrate a numerical model of that harbor so the model can be run to investigate a range of other tide and wind conditions. This would provide a detailed look at the flushing and circulation characteristics of the harbor and some insight into possible remedial efforts that may be necessary. Or the model may then be run to evaluate proposed modifications of the harbor.

(b) An alternative is to run more extensive field studies as the sole effort to evaluate conditions at a harbor. This would generally be more costly than the hybrid field-model approach, but it may provide some detail that cannot be achieved from model studies alone.

(c) Also, field studies have been done to support the general development of physical and numerical modelling techniques for the study of harbor flushing and circulation.

(d) Field measurements include those that define the hydrodynamics of a harbor and supplementary measurements to quantify harbor flushing. The former include measurements of tide levels inside and outside the harbor, current velocity measurements at the entrance to quantify flow rates into and out of the harbor, and flow velocity measurements throughout the harbor and/or drogue studies to define circulation patterns in the harbor. If tidal flushing is the primary concern, these measurements would be conducted on days when the wind velocity is low. Otherwise, a directional anemometer would also be used to measure the wind speed and direction.

(e) To determine exchange coefficients throughout the harbor and the harbor's flushing efficiency, the harbor would be uniformly seeded with a harmless detectable solute such as a fluorescent dye and then sampled periodically at several points in the harbor for a period of several tidal cycles. Initial and subsequent dye concentrations (see Equation II-7-20) can be measured in situ by a standard fluorometer. The dye Rhodamine WT has been used in a number of harbor flushing studies (see Callaway (1981) and Schwartz and Imberger (1988)).

II-7-7. Vessel Interactions

a. Vessel-generated waves.

(1) As a vessel travels across the water surface, a variable pressure distribution develops along the vessel hull. The pressure rises at the bow and stern and drops along the midsection. These pressure gradients, in turn, generate a set of waves that propagate out from the vessel bow and another generally lower set of waves that propagate out from the vessel stern. The heights of the resulting waves depend on the vessel speed, the bow and stern geometry, and the amount of clearance between the vessel hull and channel bottom and sides. The period and direction of the resulting waves depend only on the vessel speed and the water depth. For a detailed discussion of the vessel wave-generating process and the resulting wave characteristics, see Robb (1952), Sorensen (1973a, 1973b), and Newman (1978).

(2) The pattern of wave crests generated at the bow of a vessel that is moving at a constant speed over deep water is depicted in Figure II-7-40. There are symmetrical sets of *diverging* waves that move obliquely out from the vessel's sailing line and a set of *transverse* waves that propagate along the sailing line. The *transverse* and *diverging* waves meet along the cusp locus lines that form an angle of 19°28' with the sailing line. The largest wave heights are found where the *transverse* and *diverging* waves meet. If the speed of the vessel is increased, this wave crest pattern retains the same geometric form, but expands in size as the individual wave lengths (and periods) increase.

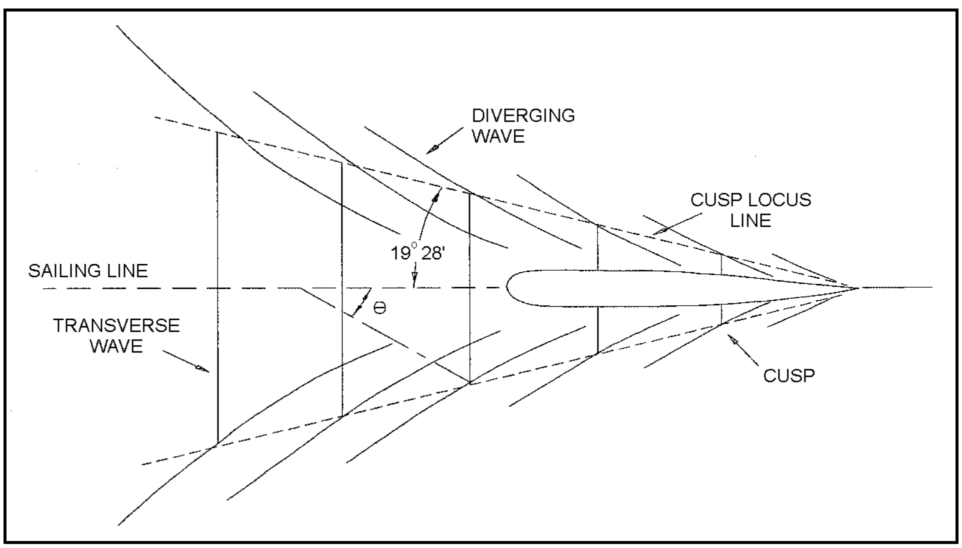

Figure II-7-40. Wave crest pattern generated at a vessel bow moving over deep water

(3) The fixed pattern of wave crests requires that individual wave celerities C be related to the vessel speed V_s by

$$C = V_s \cos\theta \qquad \text{(II-7-21)}$$

where θ is the angle between the sailing line and the direction of wave propagation (Figure II-7-40). Thus, the *transverse* waves travel at the same speed as the vessel and, in deep water, θ has a value of 35°16' for the *diverging* waves.

(4) At increasing distances from the vessel, diffraction causes the wave crest lengths to continually increase and the resulting wave heights to continually decrease. It can be shown (Havelock 1908) that the wave heights at the cusp points decrease at a rate that is inversely proportional to the cube root of the distance from the vessel's bow (or stern). *Transverse* wave heights at the sailing line decrease at a rate proportional to the square root of the distance aft of the bow (or stern). Consequently, the *diverging* waves become more pronounced with distance from the vessel.

(5) The above discussion applies to deep water, i.e. water depths where the particle motion in the vessel-generated waves does not reach to the bottom. This condition holds for a Froude number less than approximately 0.7, where the Froude number F is defined by

$$F = \frac{V_s}{\sqrt{g d}} \qquad \text{(II-7-22)}$$

(6) As the Froude number increases from 0.7 to 1.0, wave motion is affected by the water depth and the wave crest pattern changes. The cusp locus line angle increases from 19°28' to 90° at a Froude number of one. The *diverging* wave heights increase more slowly than do the *transverse* wave heights, so the latter become more prominent as the Froude number approaches unity. At a Froude number of one, the *transverse* and *diverging* waves have coalesced and are oriented with their crest perpendicular to the sailing line. Most of the wave energy is concentrated in a single large wave at the bow. Owing to propulsion limits (Schofield 1974), most self-propelled vessels can only operate at maximum Froude numbers of about 0.9. Also, as a vessel's speed increases, if the vessel is sufficiently light (i.e. has a shallow draft), hydrodynamic lift may cause the vessel to plane so that there is no significant increase in the height of generated waves for vessel speeds in excess of the speed when planing commences.

(7) For harbor design purposes, one would like to know the direction, period, and height of the waves generated by a design vessel moving at the design speed. For Froude numbers up to unity, Weggel and Sorensen (1986) show that the direction of wave propagation θ (in degrees) is given by

$$\theta = 35.27 \ (1 - e^{12(F-1)}) \qquad \text{(II-7-23)}$$

(8) Then, from Equation II-7-21, the *diverging* wave celerity can be calculated, and the wave period can be determined from the linear wave theory dispersion equation.

(9) Figure II-7-41 is a typical wave record produced by a moving vessel. Most field and laboratory investigations of vessel-generated waves (Sorensen and Weggel 1984; Weggel and Sorensen 1986) report the maximum wave height (H_m, see Figure II-7-41) as a function of vessel speed and type, water depth, and distance from the sailing line to where the wave measurement was made. Table II-7-5 (from Sorensen (1973b)) tabulates selected H_m values for a range of vessel characteristics and speeds at different distances from the sailing line. These data indicate the range of typical wave heights that might occur for common vessels and show that vessel speed is more important than vessel dimensions in determining the height of the wave generated.

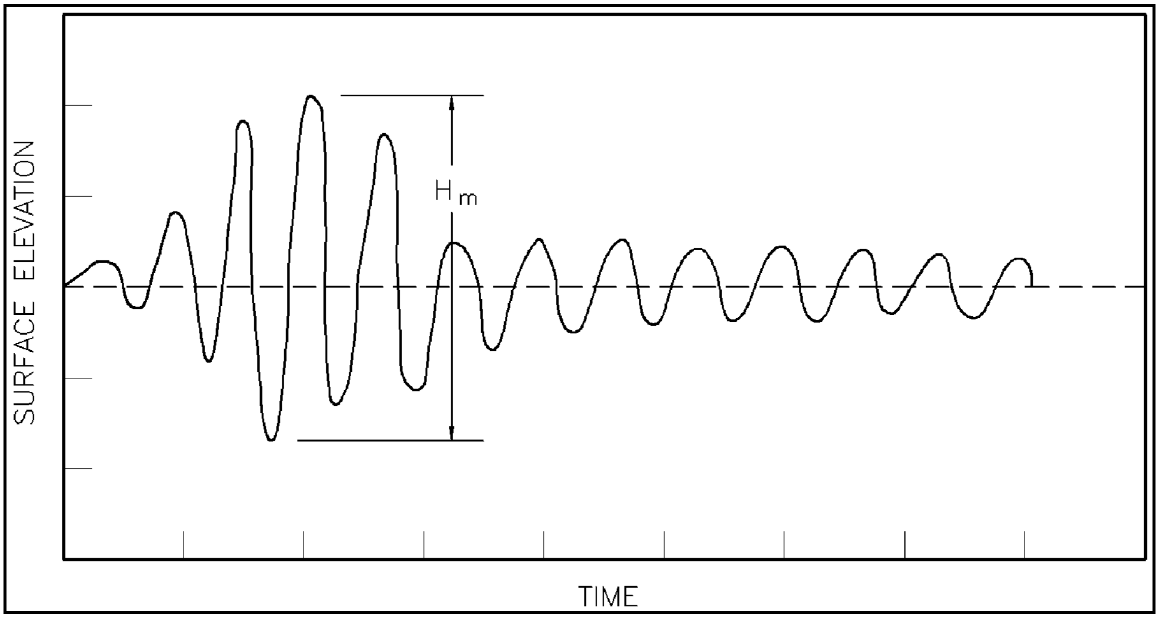

Figure II-7-41. Typical vessel-generated wave record

EXAMPLE PROBLEM II-7-5

FIND:

The period of the *diverging* waves generated by the vessel.

GIVEN:

A vessel is moving at a speed of 10 knots (5.157 m/sec) over water 5 m deep.

SOLUTION:

The vessel Froude number is

$$F = \frac{5.157}{\sqrt{9.81\ (5)}} = 0.73$$

so Equation II-7-23 gives a direction of propagation

$$\theta = 35.27\ [1 - e^{12\,(0.73-1)}] = 33.88°$$

and Equation II-7-21 gives a wave celerity

$$C = 5.157\ \cos(33.88^{\circ}) = 4.28\ \mathrm{m/s}$$

The linear wave dispersion equation can be written

$$C = \frac{g\,T}{2\pi}\ \tanh\ \frac{2\pi d}{C\,T}$$

Inserting known values for C, g, and d into the dispersion equation leads to a trial solution for T of 2.8 sec. This is a typical period for vessel-generated waves and demonstrates why floating breakwaters are usually effective in protecting against vessel waves.

(10) A number of quasi-empirical procedures for predicting vessel-generated wave heights have been published (see Sorensen (1986) and Sorensen (1989) for a summary). Most procedures are restricted to a certain class or classes of vessels and specific channel conditions. A comparison (Sorensen 1989) of predicted H_m values for selected vessel speeds and water depths showed significant variation among the results predicted by the various procedures. The best approach for design analyses appears to be to review the published vessel wave measurement data to compare with the vessel, vessel speed, and channel conditions that most closely approach the design condition and select a conservative value of H_m from these data. If this is not possible, then the values in Table II-7-5 can be used as rough estimates for the different types of vessels.

Table II-7-5
Selected Vessel-Generated Wave Heights (Sorensen 1973b)

Vessel	Speed (m/s)	H_m(m) at 30 m	H_m(m) at 150 m
Cabin Cruiser	3.1	0.2	0.1
length-7.0 m	5.1	0.4	0.2
beam-2.5 m			
draft-0.5 m			
Coast Guard Cutter	3.1	0.2	0.3
length-12.2 m	5.1	0.5	
beam-3.0 m	7.2[1]	0.7	
draft-1.1 m			
Tugboat	3.1	0.2	0.1
length-13.7 m	5.1	0.5	0.3
beam-4.0 m			
draft-1.8 m			
Air-Sea Rescue Vessel	3.1	0.1	0.2
length-19.5 m	5.1	0.4	0.3
beam-3.9 m	7.2[1]	0.6	
draft-0.9 m			
Fireboat	3.1	0.1	0.1
length-30.5 m	5.1	0.5	0.3
beam-8.5 m	7.2	0.9	0.8
draft-3.4 m			
Tanker	7.2		0.5
length-153.6 m	9.3		1.6
beam-20.1 m			
draft-8.5 m			

Note: The above data are from tests conducted at water depths ranging from 11.9 to 12.8 m.
[1] Denotes that the vessel was starting to plane.

b. Vessel motions.

(1) Response to waves.

(a) Wave action will excite a floating vessel to oscillate in one or more of six components of motion or degrees of freedom. These are translated in the three coordinate directions (surge, sway, and heave) and rotation around the three principal axes (roll, pitch, and yaw). Which of these motion components is excited and to what extent depends primarily on the direction of wave incidence relative to the primary vessel axes and on the incident wave frequency spectrum compared to the resonant frequencies of the six motion components (Wehausen 1971). If the vessel is moored, the arrangement of the mooring lines and their taughtness will influence the resonant periods and the response amplitudes of the vessel motions. If the vessel is moving, the effective or encounter period of wave agitation is the wave period relative to the ship rather than to a fixed observation point. Wave mass transport will also cause a slow drift of the vessel in the direction of wave propagation.

(b) Small vessels, such as the recreational vessels found in marinas, will commonly respond to shorter wind-wave periods. An analytical study, coupled with some field measurements for seven small boats

(Raichlen 1968), indicated that the periods of free oscillation were less than 10 sec. Larger seagoing deep-draft vessels, depending on the oscillation mode being excited, will respond to the entire range of wind-wave periods. Field measurements by van Wyk (1982) on ships having lengths between 250 and 300 m and beams of about 40 m found maximum roll and pitch responses at encounter periods between 10 and 12 sec. By properly designing the mooring system, the periods and amplitudes of vessel motion can be significantly modified.

(c) The wave-induced lateral and vertical motions of the design vessel will affect the required channel horizontal and depth dimensions, respectively. The problem of wave-induced vessel oscillations has been addressed by analytical/numerical means (Andersen 1979; Madsen, Svendsen, and Michaelsen 1980; Isaacson and Mercer 1982). These efforts usually employ small-amplitude, monochromatic waves and some limitations on vessel geometry and the incident wave directions relative to the vessel.

(d) Some field measurement programs yield valuable design information. Wang and Noble (1982) describe an investigation of vessels entering the Columbia River channel. Pitch, roll, heave, yaw, and horizontal position were measured for selected vessels as they traversed the channel. The data were analyzed statistically to define extreme limits of vessel motion for various wave and other conditions (Noble 1982). van Wyk (1982) reports on a field study of vessel response to wave action at two South African ports. The data were analyzed statistically so extreme motion probabilities could be evaluated. Other field studies of moving large vessels have been reported by Greenstreet (1982) and Zwamborn and Cox (1982). Raichlen (1968) and Northwest Hydraulic Consultants (1980) discuss field measurements of small moored vessels in marinas.

(e) Most of the major coastal engineering labs have also conducted model studies of vessel response to wave motion. Some of these tests are discussed in Mansard and Pratte (1982), Isaacson and Mercer (1982), Zwamborn and Cox (1982), and Briggs et al. (1994).

(2) Response to currents.

(a) There are several possible causes for currents in harbors and in the vicinity of harbor entrances. Wind, wave-induced radiation stress, rivers, and tides can all generate currents in the vicinity of a coastal harbor entrance. Flow from a river that enters a harbor or flows past the entrance to a harbor located in an estuary can generate significant currents. Ebb and flood tide can generate strong reversing currents through a harbor entrance. Tidally induced longshore currents around islands can cause navigation problems at harbor entrances. Long-wave resonant oscillations in harbors can generate noticeable currents at nodal points, which can seriously affect moored vessels and create hazardous navigation conditions if this location is at a place where the flow is constricted.

(b) Currents will directly affect vessel operation, particularly when they act oblique to the sailing line of the vessel. These currents are particularly troublesome when the vessel speed is low and vessel maneuverability is commensurately reduced. The situation is made even more difficult when there are strong winds acting from a different direction than the currents. Physical model studies and numerical simulations of vessel motion have been used to predict vessel paths under various wind and current conditions, particularly as vessels enter a harbor (Bruun 1989, Briggs et al. 1994). Currents can increase vessel sinkage and trim in restricted channels (see next section).

(3) Wave-current interaction.

(a) At harbor entrances, currents can also exert an indirect effect on vessel navigation through their effect on waves. Ebb currents will steepen incoming waves, making the waves more hazardous to the stability of small vessels in particular. The ebb currents may be of sufficient strength to induce wave breaking and turbulence in the entrance, a condition that is particularly hazardous to vessel operation.

(b) Bruun (1978) summarizes earlier literature and discusses the problem of sediment transport. Mehta and Özsöy (1978) found that the effects of bottom friction are important in the hydrodynamics of two-dimensional turbulent jets because it increases the rate of spreading of the jet, which has a significant effect on incident wave characteristics. Sakai and Saeki (1984) measured the effect of opposing currents on wave height transformation over a 1:30 sloping beach for a range of wave periods and steepness. They found an increase in wave height and decay rate in the presence of the opposing current. Willis (1988) conducted monochromatic wave and ebb current tests in a 1-m-wide rectangular entrance channel cut in a 1:30 sloping beach. Current measurements were averaged over 3 min to obtain a quantitative picture of the mean currents. They experienced major problems with the stability of the current field due to large-scale meandering motions.

(c) Lai, Long, and Huang (1989) conducted flume tests of kinematics of wave-current interactions for strong interactions with waves propagating with and against the current. They found the influence of the waves on the mean current profiles was small, although opposing waves would give a slightly lower current. They observed a drastic change in the spectral shape, especially higher harmonics, following wave breaking in the presence of opposing currents. Their experiments confirmed blockage of waves by a current when the ratio of depth-averaged current velocity to wave celerity without currents approaches -0.25.

(d) Raichlen (1993) conducted a laboratory investigation of waves propagating on an adverse jet to simulate the effect of ebb currents on incoming waves at a tidal inlet. He tested regular waves (depth-to-wavelength ratios from 0.086 to 0.496) for a range of relative channel entrance velocities to wave celerity for locations both upstream (20 channel widths) and downstream (15 channel widths) of the channel entrance. Wave height increased by a factor of 2.5 near the channel entrance in the presence of a current that was only 7 percent of the phase speed, primarily caused by wave refraction. He also found that the wave height decreases significantly as waves propagate up the entrance channel. Refraction and entrainment of the still fluid by the ebb current jet produces a lateral variation in the wave height across the channel width downstream of the entrance.

(e) Briggs and Green (1992) and Briggs and Liu (1993) conducted three-dimensional laboratory experiments of the interaction of regular waves with ebb currents offshore of a tidal entrance channel (6 channel widths) on a 1:30 plane beach. Current velocity to wave celerity ratios ranged from 0.06 to 0.34. Under the influence of ebb currents, waves experienced increases in steepness and corresponding wave height up to a factor of nearly 2 for currents that were 20 to 30 percent of the phase speed. As waves shoal and break, higher harmonics are formed as the wave becomes more nonlinear. Energy is transferred from the fundamental mode due to nonlinear coupling between frequencies. Briggs and Liu found that ebb currents also promote the nonlinear growth of the fundamental frequency, higher harmonics, and subharmonics of the incident wave. This shift in energy can change the response characteristics of vessels in the entrance channel.

(4) Vessel sinkage and trim.

(a) The pressure distribution that develops around the hull of a moving vessel results in an above-average pressure at the bow and stern and a below-average pressure at the midsection of the vessel. The reduced pressure at the midsection dominates and causes a net sinkage of the vessel. The vessel sinkage is also referred to as squat. Since there is usually an imbalance of upward forces between the bow and stern, the vessel will often also trim by the bow (i.e. the vessel bow is lowered relative to the stern) or by the stern.

(b) Sinkage and trim of a vessel in a navigation channel depend on the factors that control the pressure distribution along the vessel hull. Primarily, these are the vessel speed, the ratio of the channel cross section area to the vessel wetted cross section area (known as the section coefficient), and the ratio of the water depth to the vessel draft. Other factors that might affect sinkage and trim include the vessel hull geometry, the at-rest trim of the vessel, the cross-section geometry of the channel, the sailing line of the vessel relative to the centerline of the channel, vessel acceleration or deceleration, the presence of currents in the channel, and the passing of other vessels in the channel.

(c) A wide variety of analytical, quasi-analytical, and empirical methods for predicting vessel sinkage and a few for predicting vessel trim have been published (Garthune et al. 1948, Constantine 1960, Tuck 1966, Tothill 1967, Sharp and Fenton 1968, Dand and Furgeson 1973, McNown 1976, Beck 1977, Gates and Herbich 1977, Eryuzlu and Hausser 1978, Blauuw and van der Knapp 1983, Ferguson and McGregor 1986). The earliest and most basic approach to predicting vessel sinkage employs the one-dimensional energy and continuity equations. This approach gives generally acceptable results for uniform channels and vessel hull geometries that are not too irregular. The continuity and energy equations are written between a point ahead of the vessel and a point at the vessel midsection. The water surface drawdown is thus calculated and assumed equal to the vessel sinkage. The results for a rectangular channel cross section are presented below; for a trapezoidal channel cross section see Tothill (1967) and for a parabolic channel cross section, see McNown (1976).

(d) Consider a vessel in a channel with the relevant dimensions as defined in Figure II-7-42 where b is the channel width, A_m is the vessel's midsection wetted cross-section area, the undisturbed water depth is d, and the vessel drawdown is Δd. V_s and g are the vessel speed and the acceleration of gravity as defined earlier. The continuity and energy equations in terms of the Froude number F, dimensionless drawdown D, and vessel blockage ratio S are solved by

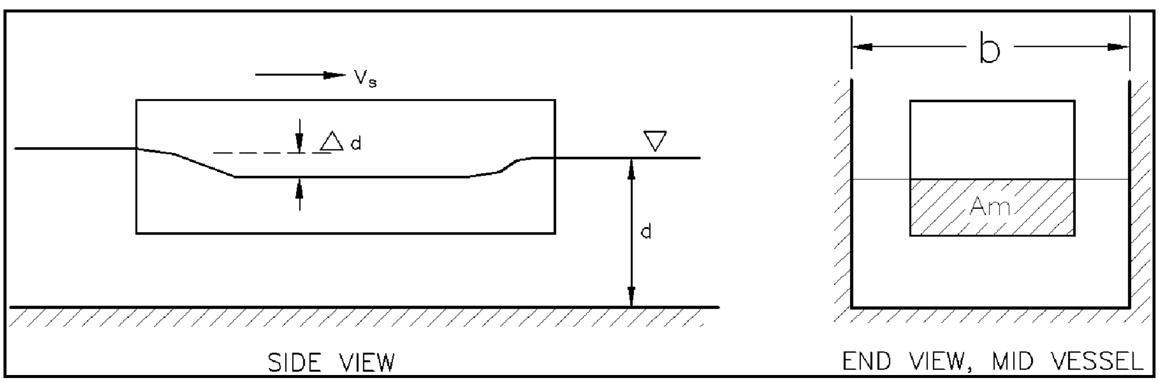

Figure II-7-42. Definition of terms, vessel drawdown

$$F = \sqrt{\frac{2D(1-D-S)^2}{1-(1-D-S)^2}} \qquad \text{(II-7-24)}$$

where

$$F = \frac{V_S}{\sqrt{gd}} \qquad D = \frac{\Delta d}{d} \qquad S = \frac{A_m}{bd}$$

(e) Figure II-7-43 plots F versus D for selected values of S. Given the channel cross-section dimensions, the water depth, the vessel speed, and the midsection wetted cross-section area of the vessel, D can be determined from the figure. This, in turn, yields the water surface drawdown Δd, which is taken as the vessel sinkage.

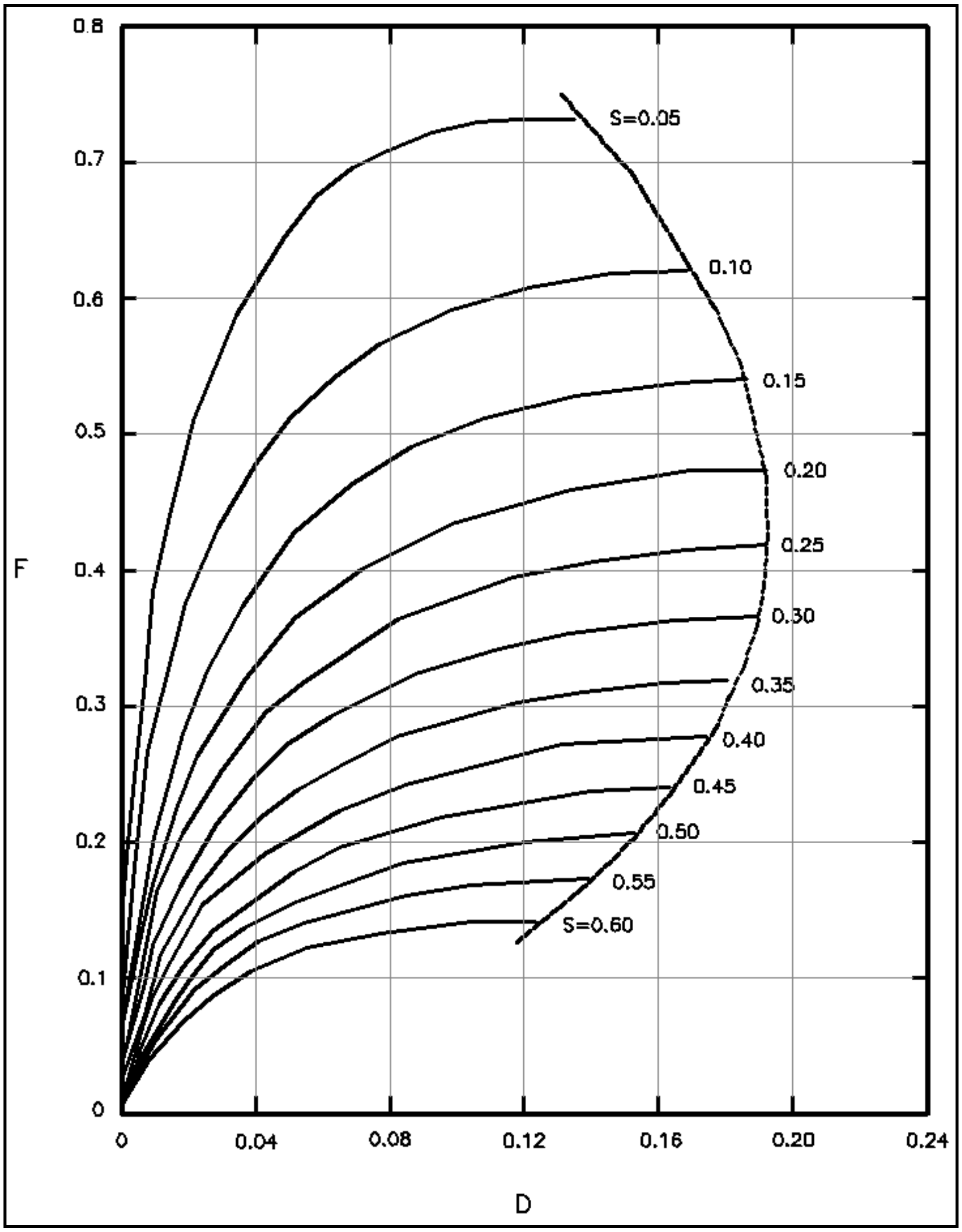

Figure II-7-43. Vessel sinkage prediction

(f) Design of safe channel depths is a function of the loaded draft of the ship, vessel sinkage, minimum underkeel clearance, and effect of pitch and roll in outer channels exposed to wave and current conditions (Herbich 1992).

(g) A self-propelled vessel cannot exceed the critical speed (see Constantine (1960)). However, a vessel can be towed faster than the critical speed, the result being the generation of a bore wave that propagates ahead of the vessel. Before reaching the critical speed, the vessel sinkage increases rapidly. If the initial vessel under-keel clearance is small, the vessel may hit bottom before coming close to the critical speed. Also, near the critical speed, there is a sharp increase in the power required to propel the vessel.

EXAMPLE PROBLEM II-7-6

FIND:

The vessel sinkage and return flow velocity between the vessel hull and the channel bottom and sides.

GIVEN:

A C9 containership has a length of 262 m, a beam of 32 m, and a fully loaded draft of 12 m. The C9 containership with a midsection wetted cross section area of 384 m^2 is moving at a speed of 6 knots (3.09 m/s) in a channel 137 m wide and 15 m deep. This is a typical scenario for deep-draft vessels entering a harbor through a one-way entrance channel.

SOLUTION:

The vessel Froude number is

$$F = \frac{3.09}{\sqrt{9.81\ (15)}} = 0.26$$

and the blockage ratio is

$$S = \frac{384}{137(15)} = 0.19$$

From Figure II-7-43 at the intersection of F = 0.26 and S = 0.19, the dimensionless drawdown is approximately D = 0.02. The vessel sinkage is then given by

$$\Delta d = 15(0.02) = 0.30 \text{ m}$$

The return velocity is calculated from Equation II-7-25 as

$$V_r = 3.09 \left[\frac{137(15)}{137(15-0.3)-384} - 1 \right] = 0.81 \text{ m/s}$$

Thus, channel depths must include additional clearance to accommodate the vessel drawdown and a substantial return velocity flow can lead to scour along the channel banks.

(h) As a vessel travels in a channel, continuity of flow causes a return flow velocity to develop between the vessel hull and the channel bottom and sides. This return flow velocity V_r can be calculated for a rectangular channel and vessel cross section (as depicted in Figure II-7-42) from

$$V_r = V_s \left[\frac{b\,d}{b\,(d - \Delta d) - A_m} - 1 \right] \qquad \text{(II-7-25)}$$

(i) Particularly for vessel/channel conditions that produce a large blockage ratio (*S*) and for high vessel speeds, a substantial return flow velocity can develop. Channel bottom scour and damage to reveted channel sides may result.

(5) Ship maneuverability in restricted waterways.

(a) The pressure distribution along the hull of a vessel will also cause lateral forces and horizontal moments to act on the vessel when it passes another vessel or moves in close proximity to a channel bank or other large structure. These effects affect all sizes of ships, but are particularly dangerous for larger vessels. Figure II-7-44 shows a pressure field for moving vessels, where the plus and minus signs indicate the relative pressures along the side of the hull.

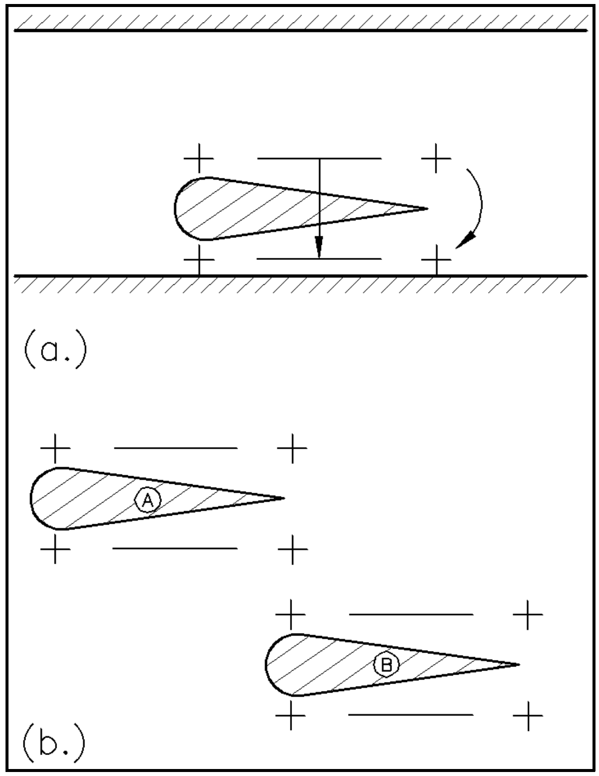

Figure II-7-44. Pressure fields for moving vessels (vessels moving left to right)

(b) Figure II-7-44a shows a vessel sailing close to a channel bank. Owing to the "Bernoulli effect," larger positive and negative pressures occur on the side closest to the channel bank, with the negative pressure dominating to draw the vessel toward the bank and the larger bow pressure than stern pressure causing the bow to rotate (yaw) away from the bank. Lateral force and yawing moment increase as the vessel sails closer to the bank and they are approximately a function of the vessel speed squared. Manipulation of the ship's rudder can correct for these forces, but it is difficult to travel close to a channel bank for any long period of time (Kray 1970).

(c) Figure II-7-44b shows two similar vessels, with vessel A passing vessel B in unrestricted water. For the positions shown, the bow of vessel A and the stern of vessel B would deflect outward because of the positive pressures at both bow and stern. When the ships are even, they would be drawn together because of the negative pressures midships, and their bows would be deflected slightly apart because of the positive pressures at the bows. And as vessel A completes passing vessel B, the stern of B and the bow of A would be deflected outward. Thus, the interacting forces and moments are complex, continually changing while the ships are in the proximity of each other, and dependent on hull sizes and geometries; vessel speeds, directions, and lateral separation; and water depth. Vessel interaction effects are more significant for vessels that have a large cross-section area relative to the channel cross-section area and for higher vessel speeds.

(d) The effects of vessel interaction have been studied for specific conditions by carrying out model studies (e.g. Taylor 1909, Robb 1949, Garthune et al. 1948, Delft Hydraulics Laboratory 1965, Moody 1970, Dand 1976). Some analytical studies that allow calculation of the resulting forces and moments, but not the vessel response, were conducted by Silverstein (1958), Hooft (1973), Tuck and Newman (1974), and Dand (1976).

(e) Vessel interactions with other vessels and with the channel bank must be accounted for in determining required navigation channel widths. For example, guidance given in Engineer Manual (EM) 1110-2-1613, which specifies channel width as a function of the design vessel beam dimension for various channel conditions, includes these effects. The total channel width consists of a maneuvering lane, bank clearance, and ship clearance, if two-way traffic is involved. This specification is based on model studies of large vessels in deep-draft navigation channels and discussions with ship pilots (Garthune et al. 1948).

c. Mooring.

(1) Wave forcing mechanism.

(a) Infragravity waves (wave periods typically between 25 and 300 sec) force long-period oscillations or seiche in harbors. If the natural period of the ship corresponds to a harbor resonance mode and they are moored in the vicinity of the node, excessive ship motion can prevent loading and unloading of the ship for a number of days. In some cases, extensive damage to the ship and pier can result if the mooring lines fail.

(b) Infragravity energy can be divided into bound and free wave energy. Bound or forced infragravity waves are nonlinearly coupled to wave groups, traveling at the group velocity of the wind waves, and phase locked to sea and swell waves. Free infragravity waves radiate to and from deep water after being reflected from the shoreline or are generated by nonlinear interactions and wave breaking of incident wind waves and are refractively trapped in shallow water, propagating in the longshore direction. According to numerous investigators (Herbers et al. 1992; Elgar et al. 1992; Okihiro, Guza, and Seymour 1992), bound and free wave energies increase with increasing swell energy and decreasing water depth. Bound wave contributions are usually more significant when energetic swell conditions exist, but free waves dominate when more moderate conditions prevail.

(2) Mooring configurations.

(a) A vessel moored in a harbor or at some point offshore commonly has one of three types of mooring arrangements:

- A single-point mooring where the vessel is tied to a buoy by a single line from the bow and is thus free to rotate around the buoy (i.e. weathervane) in response to environmental forces.

- A multiple- point mooring where the ship is tied by several fore and aft lines to anchors or buoys.

- A conventional pier anchorage, where the vessel is tied fore and aft to the pier and separated from the pier by a fendering system.

(b) For a deep-draft vessel at a pier, the mooring line system will typically consist of 8 to 12 lines in a symmetrical pattern, half from the bow and half from the stern of the ship. One to two *breast* lines are positioned on both bow and stern. The breast line(s) is perpendicular to the ship and dock and presses the ship against the dock and fenders. Two *head* lines make an angle of 60-70 deg to the *breast* line and go forward from the bow. Two *stern* lines are analogous to the *head* lines, but originate from the stern of the ship. These four lines are on the order of 100 ft long between ship and dock attachment points. Finally, two or four *spring* lines make an angle of 85 deg to the *breast* line and go toward midships. These lines can vary in length from 100 to 200 ft. The *spring* lines, in combination with the *breast* lines, provide the most efficient ship mooring. The deck of the vessel is typically 3 to 8 m above the pier, with the bow being higher than the stern.

(3) Mooring lines.

(a) Mooring lines are made from steel, natural fibers, and synthetic materials. Steel ropes may be made of different strength grades and galvanized for protection against corrosion. Natural fibers include manilla, sisal, and coir. Commonly used synthetic materials are nylon, dacron, polypropylene, Kevlar, and Karastan (Herbich 1992).

(b) Synthetic lines are easy to handle, do not corrode, and have excellent strength-to-weight ratios. Different construction types include stranded, plaited, braided, and parallel yarns. Stranded is the least satisfactory for mooring lines because it tends to unlay under free end conditions. Each has different mechanical properties that make it appropriate for different applications. These include strength, weight, stretch, endurance, and resistance to abrasion and cuts.

(c) Care should be taken not to mix different materials and lengths in mooring arrangements (Oil Companies International Marine Forum (OCIMF) 1978). Elasticity is a measure of a mooring line's ability to stretch under load. It is a function of material, diameter, and length. The ultimate breaking strength has been related to the square of the nominal rope diameter (Wilson 1967). If two lines of different elasticity but similar lengths and orientations are combined at the same point, the stiffer one will assume more of the load. Also, lines of different length will carry different amounts of the total load. Thus, one of the lines may be near breaking while the other one is carrying almost no load.

(4) Fenders. Fenders are like bumpers on cars, designed to protect vessels and piers during berthing and mooring against forces due to winds, waves, and currents. They are designed to absorb impact energy of the vessel through deflection and dissipation. Some respond very fast and violently and others more slowly. The latter are the more desirable because they produce smaller fender forces. Highly elastic, recoiling type fenders should be replaced with the non-recoiling type if possible. Fenders can be continuous or placed in certain areas where vessels land. The mooring system should be designed based on the combined response of mooring lines and fenders to ensure that resonance effects with the environmental forces are minimized. The interested reader should consult Bruun (1989) for additional information on types, materials, characteristics, selection, forces, deformation, and energy absorption of fenders.

(5) Surge natural period.

(a) For moored vessels at a dock or quay, surge is one of the most important parameters to consider. Ranges of allowable movements for different vessels have been given by Bruun (1989).

(b) The motion of a moored ship in surge can be described by the motion of a linear system with a single degree of freedom. Restoring or reaction forces due to the change in position, velocity, and acceleration of the ship from equilibrium are assumed linear. The exciting force is due to the drag force of the water flowing past the ship. The motion of the ship in surge is assumed to be independent of other directions of motion. Damping is assumed to be small for the low-frequency motions of a ship in surge. Solving for the undamped natural period in surge T_s

$$T_n = 2\pi \sqrt{\frac{m_v}{k_{tot}}} \tag{II-7-26}$$

(c) The virtual mass of the ship m_v is the sum of the actual mass or displacement of the ship m and the added mass m_a due to inertial effects of the water entrained with the ship. For a ship in surge, m_a is approximately 15 percent of the actual mass m, which is based on the ship's displacement

$$m_v = m + m_a = 1.15\,\mathrm{m} \qquad \text{(II-7-27)}$$

(d) A mooring system is composed of many lines, but only those in tension contribute to the stiffness or effective spring constant k_{tot} given by

$$k_{tot} = \sum_n k_n \sin\theta_n \cos\varphi_n \qquad \text{(II-7-28)}$$

where the index n sums over all head, stern, and spring lines in tension during surge motion (breast lines are conservatively assumed to provide no restoring force in surge), θ_n is the angle the line makes in the horizontal plane with the perpendicular to the ship, and φ_n is the angle the line makes in the vertical plane between the ship and the dock.

(e) For a taut mooring line in which sag is negligible and deflections are small, the individual stiffness k_n is defined by

$$k_n = \frac{T_n}{\Delta l_n} \qquad \text{(II-7-29)}$$

where T_n is the axial tension or load and Δl_n is the elongation in the mooring line. The elastic behavior of fiber ropes is difficult to ascertain since it is a function of material, construction, size, load and load history, time, and environmental conditions. Typically, manufacturers supply elongation curves based on experimental data, which show percent elongation ε_n as a function of load as a percent of the breaking strength of the mooring line (Figure II-7-45). A new rope undergoes construction stretch or permanent strain, which occurs when initial loading places the fibers in paths different from their initial construction. Elastic stretch occurs for subsequent loading and is repeatable each time the rope is loaded. Under high loads for a long time, the rope may undergo cold flow of the fibers and eventually break. Thus, previously elongated rope does not stretch as much as new rope and separate elongation curves may be provided. Percent elongation is related to Δl_n by

$$\varepsilon_n = 100\left(\frac{\Delta l_n}{l_n}\right) \qquad \text{(II-7-30)}$$

where l_n is the length of the mooring line. This formulation assumes that cable dynamics can be neglected, and that the natural frequency of the mooring line in longitudinal and transverse vibration is much higher than the surge frequency of the ship.

(f) Therefore, the natural period of a moored ship in surge is a function of displacement, and number, type, length, size, and tension of the mooring lines. As the ship is off-loaded, displacement of the ship will decrease and this will change the ship response characteristics. Proper ballasting can be used to prevent surge conditions from developing. If this is not possible, other remedies can be sought. The natural period of the moored ship can be adjusted by changing the mooring line configuration or tension. Increased tension will make the moored ship stiffer and will reduce its resonant period of oscillation. A decrease in the mooring line tension will make the moored ship less prone to shorter-period resonant modes. If this is not practical, the number and type of mooring lines can be changed to affect the response of the moored ship.

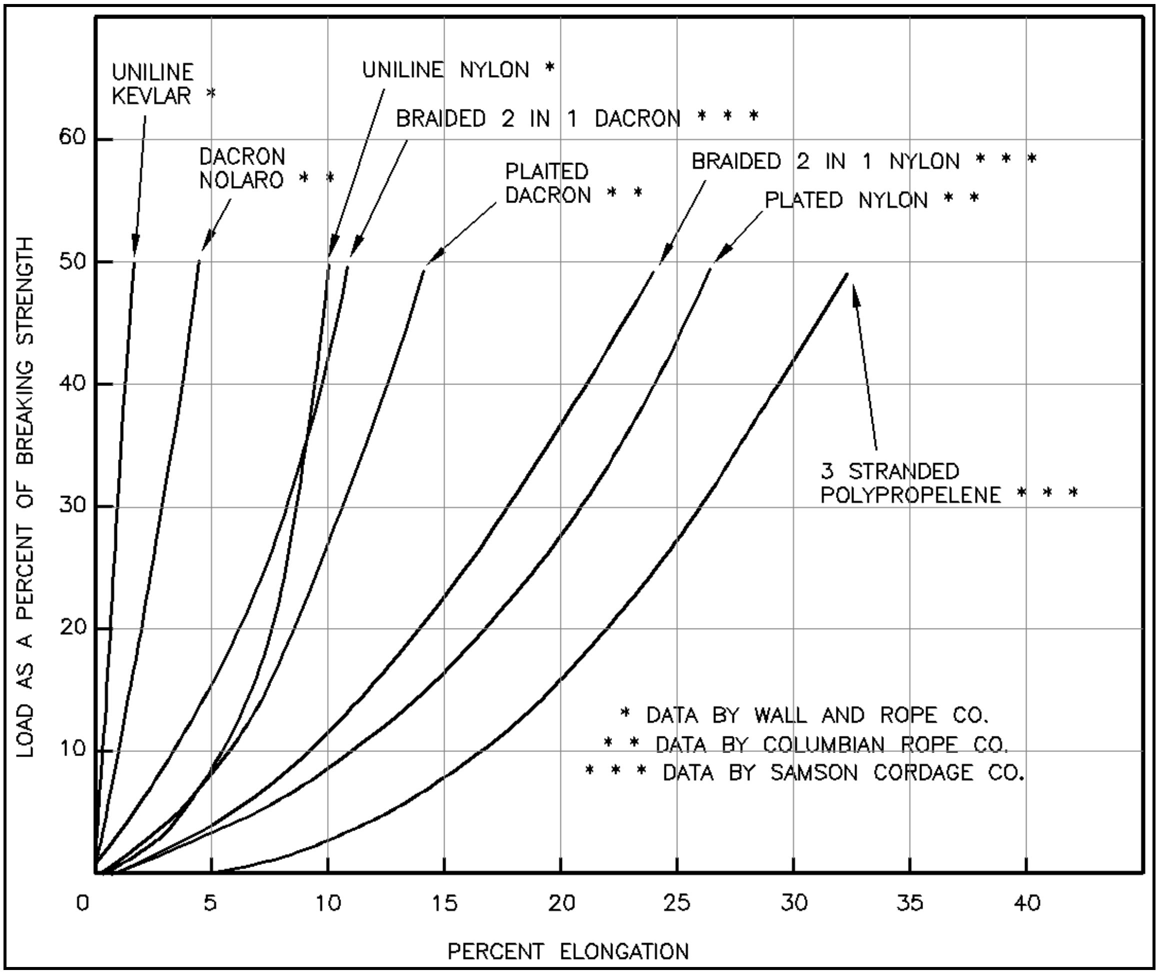

Figure II-7-45. Mooring fiber rope elongation curves

(6) Mooring forces.

(a) Design of any of these systems requires that the primary hydrodynamic loads on the vessel caused by the wind, currents, and waves be determined, usually on a probabilistic basis. Other loads that may be important in certain situations are ice forces and forces induced by passing vessels. The appropriate forces are employed in a dynamic analysis of the mooring system to determine expected loads in the mooring lines and on the fender systems. This analysis can be done by a physical model study or by a computer simulation of the system dynamics equations (see Bruun (1989) and Gaythwaite (1990)). Detailed discussions of the primary vessel mooring forces, those caused by the wind, currents, and waves, can be found in Tsinker (1986), Bruun (1989), and Gaythwaite (1990).

(b) The wind load is determined from the usual drag equation

$$F_w = \frac{1}{2} \rho_a C_D A \, V_{10}^2 \qquad \text{(II-7-31)}$$

where F_w is the drag force due to the wind, ρ_a is the air density, C_D is a drag coefficient, A is the projected area of the vessel above the waterline, and V_{10} is the wind speed at the standard elevation of 10 m above the water's surface.

EXAMPLE PROBLEM II-7-7

FIND:

The natural period of the vessel in surge for used mooring lines in good condition.

GIVEN:

A C9 containership is moored at a pier in Barbers Point Harbor, Oahu, Hawaii. Its fully-loaded displacement is 54,978 long tons (55,860,231 kg). Karat Estalon fiber ropes with a 7-1/2-in. circumference (6.3-cm-diam) are used for the two head, two stern, and two spring lines. Head and stern lines are 30.5 m long and make an angle of 70 deg with the perpendicular breast lines. The spring lines are 45.7 m long and form an angle of 85 deg with the breast lines. The tension in these lines is maintained at 20 tons (177,900 N). The deck of the C9 is assumed to be 7 m above the dock at the bow and 4.5 m at the stern.

SOLUTION:

Virtual mass is calculated from Equation II-7-27

$$m_v = 1.15(55{,}860{,}200) = 64{,}239{,}200 \text{ kg}$$

The next step is to calculate the effective spring constant. Karat lines are manufactured by Columbian Rope Company, Guntown, MS, under license from Akzo, Holland. Estalon is a fiber that is a copolymer of polyester and polypropylene. According to manufacturer's literature, the breaking strength for Karat ropes is 526,000 N. The load as a percent of breaking strength is

$$Load = 100\left[\frac{177{,}900}{526{,}000}\right] = 33.8\%$$

From the elongation chart for Karat lines (not shown), the percent elongation is 8.7 percent. The elongation for the head and stern lines is the same and is calculated from Equation II-7-30

$$\Delta l_{Hd} = \Delta l_{St} = \frac{8.7(30.5)}{100} = 2.7 \text{ m}$$

Likewise, the elongation for the spring lines is given by

$$\Delta l_{Sp} = \frac{8.7(45.7)}{100} = 4.0 \text{ m}$$

Example Problem II-7-7 (Continued)

Example Problem II-7-7 (Concluded)

Individual stiffness for the head and stern lines is calculated from Equation II-7-29

$$k_{Hd} = k_{St} = \frac{177{,}900}{2.7} = 65{,}900 \text{ N/m}$$

Similarly, the stiffness for individual spring lines is

$$k_{Sp} = \frac{177{,}900}{4.0} = 44{,}500 \text{ N/m}$$

The vertical angles from the bow, stern, and spring lines are

$$\varphi_{Hd} = \arcsin\left[\frac{7.0}{30.5}\right] = 13^\circ$$

$$\varphi_{St} = \arcsin\left[\frac{4.5}{30.5}\right] = 8^\circ$$

$$\varphi_{Sp} = \arcsin\left[\frac{4.5}{45.7}\right] = 6^\circ$$

When the ship surges forward, the two stern lines and a spring line provide restoring forces. Similarly, when the surge is in reverse, two head lines and a spring line provide the restoring forces. The effective spring constant is calculated both ways and averaged from Equation II-7-28

$$\begin{aligned} k_{tot} &= 2(65{,}900)\ \sin 70^\circ\ \cos 8^\circ + 44{,}500\ \sin 85^\circ\ \cos 6^\circ \\ &= 122{,}600 + 44{,}100 = 166{,}700 \text{ N/m} \end{aligned}$$

$$\begin{aligned} k_{tot} &= 2(65{,}900)\ \sin 70^\circ\ \cos 13^\circ + 44{,}500\ \sin 85^\circ\ \cos 6^\circ \\ &= 120{,}700 + 44{,}100 = 164{,}800 \text{ N/m} \end{aligned}$$

$$k_{tot} = \frac{166{,}700 + 164{,}800}{2} = 165{,}750 \text{ N/m}$$

Finally, the natural period in surge is calculated from Equation II-7-26

$$T_s = 2(3.14)\sqrt{\frac{64{,}239{,}200}{165{,}750}} = 124 \text{ sec}$$

If the rope had been new, the percent elongation would have been higher at 10.7 percent. This would have resulted in a slightly higher surge natural period of approximately 136 sec.

(c) During a storm, it is likely that some water will be entrained in the air. This would significantly increase the air density. Some investigators have argued that the entrained water will also slow down the air so there would be no net increase in wind drag. This issue is still unresolved. Current practice is to neglect entrained water when specifying the air density in the wind drag calculation.

(d) Values for the drag coefficient depend on the vessel geometry and orientation to the wind, and have been determined from wind tunnel tests. C_D values show significant variation, so reference should be made to Benham et al. (1977), Gaythwaite (1990), Isherwood (1973), Naval Facilities Engineering Command (1968), Owens and Palo (1981), and Palo (1983) for information on drag coefficients for a variety of vessels. These references also give some information on projected areas for common types of vessels.
Table II-7-6 lists drag coefficients for wind (Bruun 1989).

Table II-7-6
Drag Coefficients for Wind Force

Wind Direction	C_D		
	Max.	**Min.**	**Mean**
Crosswise	1.40	0.80	1.11
Bow	1.04	0.62	0.82
Stern	1.02	0.64	0.77

(e) The wind speed at the standard elevation (10 m) is commonly used because this would be a good reference elevation for most larger vessels. If the center of pressure of the vessel is at a significantly different elevation than 10 m, the 1/7th power velocity profile law may be used to correct the wind velocity. It is defined by

$$V_z = V_{10} \left(\frac{z}{10} \right)^{0.11} \tag{II-7-32}$$

where V_z is the velocity at the desired elevation z. Typically, a 50-year return period wind speed is used or the limiting wind speed for which a vessel might remain moored would be used.

(f) The gustiness of the wind must also be considered; i.e., what duration wind gust is sufficient to envelop the vessel. To account for gustiness, the drag coefficient is often increased by a factor of about 1.4 (Tsinker 1986).

(g) Commonly, current drag forces are determined with less certainty than wind drag forces. Current speeds and directions at the mooring site may be difficult to predict, particularly in a harbor having a complex layout. Currents may be continually shifting if dominated by the tide or river flow. The Reynolds number for currents acting on a vessel is usually in the fully turbulent region, but often close to the transition point where drag coefficients show a wider range of scatter. The vessel draft and resulting bottom clearance can also have a significant impact on the resulting drag force. Gaythwaite (1990) presents several sources for current drag coefficient and vessel projected area information. Seelig, Kreibel, and Headland (1992) have published a recent analysis of new scale-model drag studies and other data collected over the past five decades.

EXAMPLE PROBLEM II-7-8

FIND:

The wind drag for a Beaufort 5 fresh breeze of 20 knots (10.31 m/s) at an angle of 30 deg to the wind. Assume gustiness can be accounted for by applying a factor of 1.20 to the wind speed. Beaufort 5 is usually the limiting wind for port operations of loading and unloading.

GIVEN:

A C9 containership is moored at a pier with an asymmetrical container distribution of 5 high in the bow half of the vessel and none in the aft portion. The useable length of the ship for cargo handling is 246 m. The height above the water is 10.9 m. The containers are 2.7 m tall.

SOLUTION:

The forward and aft areas exposed to the wind are

$$A_{aft} = \frac{246}{2}\, 10.9 = 1{,}340 \text{ m}^2$$

$$A_{forward} = 123\left[10.9 + 5(2.7)\right] = 3{,}000 \text{ m}^2$$

The net effective area is then

$$A_{eff} = \left[1{,}340 + 3{,}000\right] \sin 30^\circ = 2{,}170 \text{ m}^2$$

The wind speed, including a gustiness factor, is

$$V_w = 1.20(10.31) = 12.4 \text{ m/s}$$

Substituting these values into Equation II-7-31, we get

$$F_w = \frac{1}{2}(1.2)(1.0)(2{,}170)(12.4)^2 = 200 \text{ kN}$$

where we have assumed $\rho_a = 1.2$ kg/m^3 at 20 $^\circ$C and $C_D = 1.0$ as a reasonable value since the mean drag coefficient for bow and transverse winds varies between 0.82 to 1.11.

(h) Longitudinal current loads on ships are taken from procedures by NAVFAC Design Manual DM26.5. The total longitudinal current load $F_{c,tot}$ is composed of form drag $F_{c,form}$, skin friction $F_{c,fric}$, and propeller $F_{c,prop}$ drag components. All three components have similar equations.

$$F_{c,tot} = F_{c,form} + F_{c,fric} + F_{c,prop} \qquad \text{(II-7-33)}$$

(i) Form drag is due to the flow of water past the vessel's cross-sectional area and is defined as

$$F_{c,form} = -\frac{1}{2}\, \rho_w\, C_{c,form}\, B\, T\, V_c^2 \cos\theta_c \qquad \text{(II-7-34)}$$

where ρ_w is the water density, $C_{c,form}$ is the form drag coefficient = 0.1, B is the vessel beam, T is the vessel draft, V_c is the average current speed, and θ_c is the angle of the current relative to the longitudinal axis of the vessel. Skin friction drag is due to the flow of water over the wetted surface area of the vessel and is given by

$$F_{c,fric} = -\frac{1}{2} \rho_w C_{c,fric} S V_c^2 \cos\theta_c \qquad \text{(II-7-35)}$$

where $C_{c,fric}$ is the skin friction coefficient and S is the wetter surface area of the vessel. The skin friction coefficient is a function of the Reynolds number R_n

$$C_{c,friction} = \frac{0.075}{(\log_{10} R_n - 2)^2} \qquad \text{(II-7-36)}$$

$$R_n = \frac{V_c L_{wl} \cos\theta_c}{\nu} \qquad \text{(II-7-37)}$$

where L_{wl} is the waterline length of the vessel and ν is the kinematic viscosity of water. The wetted surface area is defined as

$$S = (1.7 T L_{wl}) + \frac{35 D}{T} \qquad \text{(II-7-38)}$$

where D is the displacement of the vessel.

(j) Finally, the propeller drag is due to the form drag of the propeller with a locked shaft and is given by

$$F_{c,prop} = -\frac{1}{2} \rho_w C_{c,prop} A_p V_c^2 \cos\theta_c \qquad \text{(II-7-39)}$$

where $C_{c,prop}$ is the propeller drag coefficient = 1 and A_p is the expanded or developed blade area of the propeller defined as

$$A_p = \frac{L_{wl} B}{0.838 A_r} \qquad \text{(II-7-40)}$$

(k) The area ratio A_r is the ratio of the waterline length times the beam to the total projected propeller area. Typical values range between 100 for a destroyer and 270 for a tanker.

(l) Thus, to calculate current loads, the following input parameters are needed: the vessel's beam, draft, waterline length, displacement, and propeller area ratio; and average current speed and direction.

(m) It is difficult to evaluate wave loadings on a moored vessel. Both wind-wave and long-period waves are oscillatory; so there is a complex interaction with the mooring system dynamics. This interaction depends on the incident wave frequencies, the vessel added mass and drag characteristics, and the elastic characteristics of the mooring lines and fender system. The vessel can respond in one or more of the six modes of oscillation (see above). Rather than an analytical treatment of the problem in which actual wave loads are determined, scale model testing is often employed. In the latter, the system response in terms of mooring line loads, fender loads, and vessel response modes are directly determined for given incident wave spectra. Sarpkaya and Isaacson (1981) and Gaythwaite (1990) discuss this further.

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II-7-9. Definitions of Symbols

α	Angle a surface-piercing sloped plane forms with the horizontal [deg]
β	Angle between the breakwater and the radial distance from the breakwater tip to the point where the diffraction coefficient (K') is to be determined (Figure II-7-2) [deg]
Δd	Vessel drawdown [length]
Δl_n	Elongation in the mooring line [length]
ε_n	Percent elongation in a mooring line
θ	Angle between the sailing line and the direction of wave propagation [deg]
θ_c	Angle of the current relative to the longitudinal axis of the vessel [deg]
θ_n	Angle a mooring line makes in the horizontal plane with the perpendicular to the vessel [deg]
ν	Kinematic viscosity of water [length^2/time]
ρ_a	Mass density of air [force-time^2/length^4]
ρ_w	Mass density of water (salt water = 1,025 kg/m^3 or 2.0 slugs/ft^3; fresh water = 1,000kg/m^3 or 1.94 slugs/ft^3) [force-time^2/length^4]
φ	Angle a mooring line makes in the vertical plane between the vessel and the dock [deg]
φ	Phase angle by which a mass displacement lags the excitation displacement [deg]
A	Amplification factor (ratio of mass displacement to excitation displacement) [dimensionless]
A	Projected area of a vessel above the waterline [length^2]
A_b	Surface area of a bay or basin [length^2]
A_c	Channel cross-sectional flow area of an inlet [length^2]
A_m	Vessel's midsection wetted cross-sectional area [length^2]
A_p	Expanded or developed blade area of a propeller (Equation II-7-40) [length^2]
A_r	Dimensionless ratio of the waterline length times the beam to the total projected propeller area
b	Channel width [length]
B	Breakwater gap (Figure II-7-6} [length]
B	Structure crest width [length]
B	Vessel beam [length]
B'	Imaginary breakwater gap [length] (Figure II-7-6)

C	Dimensionless coefficient in the Seelig equation (Equation II-7-2) for the wave transmission coefficient (Equation II-7-3)
C	Individual wave celerities created by a moving vessel (Equation II-7-21) [length/time]
$C_{c,form}$	Form drag coefficient [dimensionless]
$C_{c,prop}$	Propeller drag coefficient [dimensionless]
$C_{c,fric}$	Skin friction coefficient [dimensionless]
C_D	Coefficient of drag for winds measured at 10-m [dimensionless]
C_o , C_i	Initial concentration of some substance in the harbor water and concentration of the substance after *i* tidal cycles (Equation II-7-20)
C_r	Reflection coefficient [dimensionless]
C_t	Wave transmission coefficient [dimensionless]
C_{t0}	Coefficient for wave transmission by flow over the structure [dimensionless]
C_{tt}	Coefficient for wave transmission through the structure [dimensionless]
d	Water depth [length]
D	Dimensionless drawdown
D	Displacement of a vessel [length^3]
D_{50}	Median diameter of armor stone [length]
d_c	Channel depth [length]
d_s	Water depth at the toe of the structure [length]
E	Dimensionless average per cycle exchange coefficient, a factor for defining the effectiveness of tidally induced harbor flushing (Equation II-7-20)
F	Freeboard [length]
F	Froude number
$F_{c,form}$	Form drag of a vessel (Equation II-7-34) [force]
$F_{c,fric}$	Skin friction of a vessel (Equation II-7-35) [force]
$F_{c,prop}$	Vessel propeller drag (Equation II-7-39) [force]
$F_{c,tot}$	Total longitudinal current load on a vessel (Equation II-7--33) [force]
F_w	Drag force due to wind (Equation II-7-31) [force]
g	Gravitational acceleration [length/time^2]
h	Structure crest elevation [length]

H	Standing wave height [length]
H_d	Diffracted wave height at a point in the lee of a breakwater [length]
H_i	Incident wave height [length]
H_r	Reflected wave height [length]
H_t	Transmitted wave height [length]
I_r	Surf similarity number or Iribarren number (Equation II-7-6) [dimensionless]
k_n	Individual stiffness of a mooring line (Equation II-7-29) [force/length]
k_{tot}	Effective spring constant (Equation II-7-28) [force/length]
K'	Diffraction coefficient [dimensionless]
K'_e	Effective diffraction coefficient (Equation II-7-1) [dimensionless]
L	Wave length [length]
ℓ_B	Basin length along the axis B [length]
ℓ_c	Channel length [length]
ℓ'_c	Additional length to account for mass outside each end of the channel [length]
l_n	Length of a mooring line [length]
L_{wl}	Waterline length of a vessel [length]
m	Mass of a vessel [force]
M_0	Zero moment of the spectrum
m_a	Mass of a vessel due to inertial effects of the water entrained with the vessel [force]
m_v	Virtual mass of a vessel (Equation II-7-27) [force]
N	Water surface amplitude (Equation II-7-7) [length]
$-_O$	The subscript 0 denotes deepwater conditions
r	Radial distance from the breakwater tip to the point where the diffraction coefficient (K') is to be determined (Figure II-7-2) [length]
R	Wave runup above the mean water level [length]
R_n	Reynolds number
S	Vessel blockage ratio [dimensionless]
S	Wetted surface area of a vessel [length^2]
S_{max}	Directional concentration parameter characterizing the directional spread of the wave spectrum [dimensionless]

T	Excitation (and response) period [time]
T	Vessel draft [length]
T	Wave period [time]
T_H	Resonant period for Helmholtz mode (Equation II-7-18)[time]
T_n	Axial tension or load on a mooring line [force]
$T_{n,m}$	Natural free oscillating period (n, m is the number of nodes along the x- and y-axes of a basin [time]
T_n	Undamped natural period of a vessel (Equation II-7-26) [time]
$\overline{V}$	Average horizontal velocity at a node (Equation II-7-16) [length/time]
V_{10}	Wind speed at the standard elevation of 10 m above the water surface [length/time]
V_c	Average current speed [length/time]
V_{max}	Maximum horizontal velocity at a node [length/time]
V_r	Return flow velocity (Equation II-7-25), velocity that develops between the vessel hull and the channel bottom and sides [length/time]
V_s	Vessel speed [length/time]
V_z	Wind speed at elevation z [length/time]
W	Breakwater's characteristic dimension in the direction of wave propagation [length]
W	Channel width [length]
X	Maximum horizontal particle excursion at a node in a standing wave (Equation II-7-15) [length]
y	Vertical extent of the barrier below the still-water surface [length]

II-7-9. Acknowledgments

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