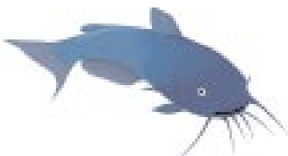
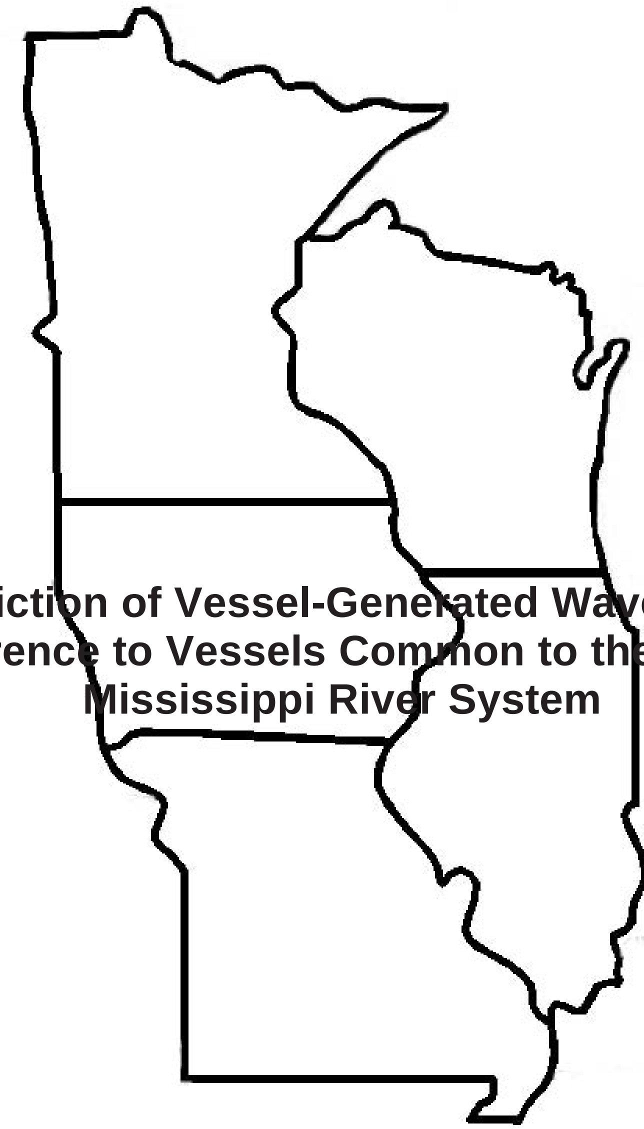
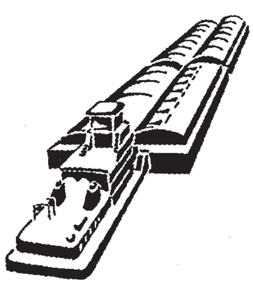
ENV Report 4

Interim Report For The Upper Mississippi River - Illinois Waterway System Navigation Study





Prediction of Vessel-Generated Waves with Reference to Vessels Common to the Upper Mississippi River System



December 1997

US Army Corps
of Engineers

Rock Island District
St. Louis District
St. Paul District

Upper Mississippi River - Illinois Waterway System Navigation Study

ENV Report 4
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Prediction of Vessel-Generated Waves with Reference to Vessels Common to the Upper Mississippi River System

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Interim report

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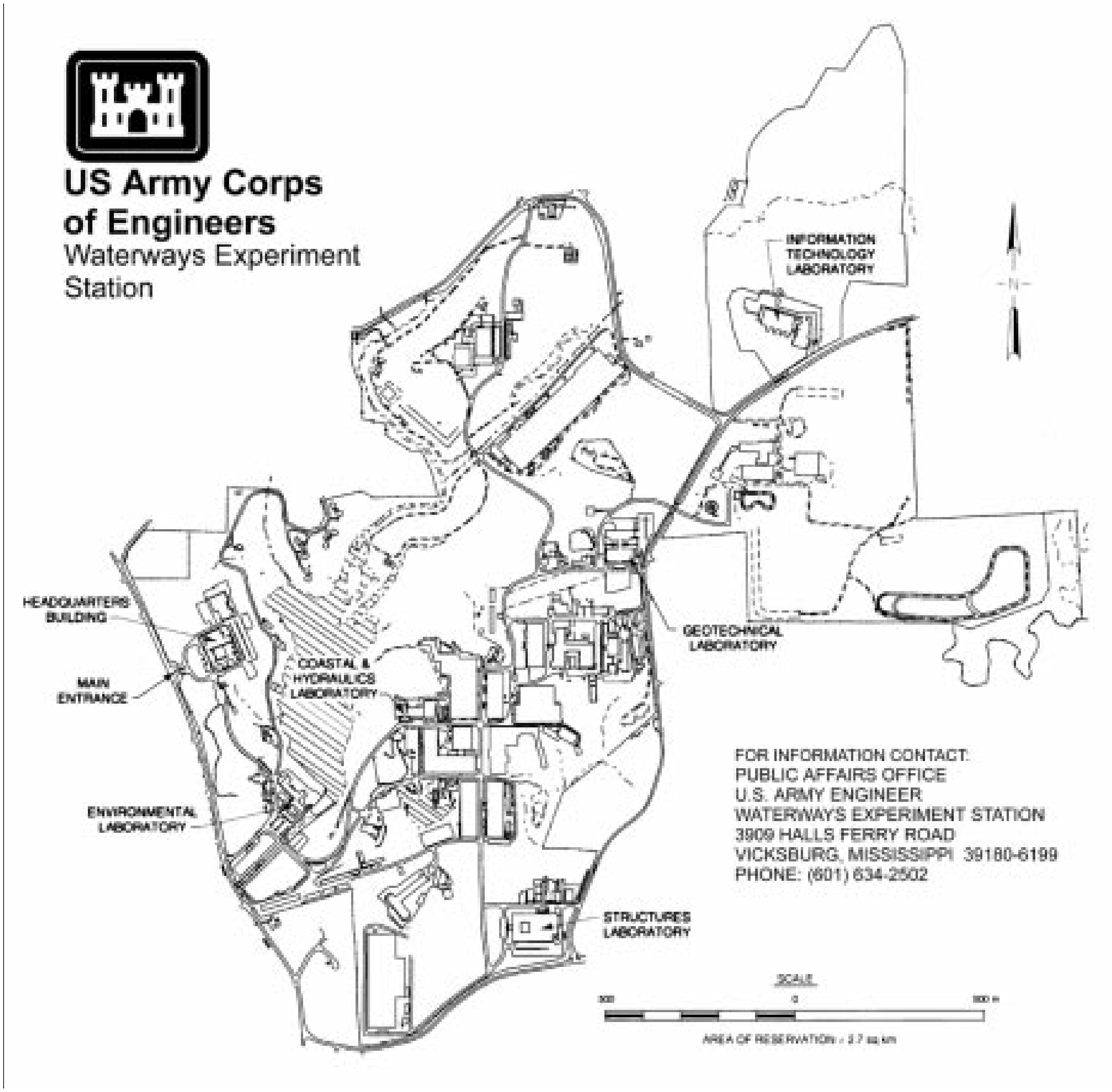

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Preface

The work reported herein was conducted as part of the Upper Mississippi River-Illinois Waterway (UMR-IWW) System Navigation Study. The information generated for this interim effort will be considered as part of the plan formulation process for the System Navigation Study.

The UMR-IWW System Navigation Study is being conducted by the U.S. Army Engineer Districts of Rock Island, St. Louis, and St. Paul under the authority of Section 216 of the Flood Control Act of 1970. Commercial navigation traffic is increasing, and in consideration of existing system lock constraints, will result in traffic delays that will continue to grow into the future. The System Navigation Study scope is to examine the feasibility of navigation improvements to the Upper Mississippi River and Illinois Waterway to reduce delays to commercial navigation traffic. The study will determine the location and appropriate sequencing of potential navigation improvements on the system, prioritizing the improvements for the 50-year planning horizon from 2000 through 2050. The final product of the System Navigation Study is a Feasibility Report, which is the decision document for processing to Congress.

The report was prepared by Dr. Robert M. Sorensen, Lehigh University, Bethlehem, PA, while under contract with the Coastal and Hydraulics Laboratory (CHL) of the U.S. Army Engineer Waterways Experiment Station (WES) in support of the UMR-IWW System Navigation Study. This report supports the recreational boating studies requested and sponsored by the U.S. Engineer District, St. Paul. The report was prepared under the direct supervision of Dr. Sandra K. Martin, Navigation Effects Group, Navigation Division, CHL, and under the general supervision of Dr. Larry Daggett, Chief, Navigation Division, Mr. Richard A. Sager, Assistant Director, CHL, and Dr. James R. Houston, Director, CHL.

At the time of publication of this report, Director of WES was Dr. Robert W. Whalin. Commander was COL Robin R. Cababa, EN.

Conversion Factors, Non-SI to SI Units of Measurement

Non-SI units of measurement used in this report can be converted to SI units as follows:

Multiply	By	Obtain
feet	0.3048	meters
horsepower (550 foot-pounds force per second)	745.7	watts
knots (international)	0.514	meters per second
miles (U.S. nautical)	1.852	kilometers
miles (U.S. statute)	1.609	kilometers

1 Introduction

In navigable waterways, owing to the relatively short fetches for wind wave generation, the free waves generated by moving vessels often produce the dominant wave action for design. In the past, several laboratory and field vessel wave measurement programs have been carried out. Based on the data from these studies, a number of empirical vessel wave prediction models have been developed. Some models have partial theoretical support. Most models are based on limited data and apply only to certain vessel types and waterway conditions. All suffer from certain limitations such as inadequate definition of the vessel bow geometry.

The objective of this report is to evaluate the literature on vessel-generated waves and, based on the literature, to present the best available model(s) for vessel wave prediction with an emphasis placed on the types of vessels that operate on the Upper Mississippi River System (UMRS).

Chapter 1 provides a review of the vessel wave-generating mechanism and the resulting pattern and characteristics of the waves generated by a moving vessel. Chapter 2 presents the available predictive models for vessel-generated waves. This chapter also evaluates those models based both on their method of development and on comparisons with appropriate field data. Chapter 2 is followed by a chapter that discusses the applicability of these models to the recreational vessels common to the UMRS. Chapter 5 summarizes the report and recommends work to be carried out to improve vessel wave prediction procedures. Appendix A is an annotated bibliography of the available literature on vessel-generated waves.

2 Vessel-Generated Waves

This chapter gives a review of the basic concepts of vessel wave generation and the pattern and characteristics of the resulting waves. For more detail see Havelock (1908), Sorensen (1966b), Sorensen (1973), and Thompson (1887).

Wave Generation

As a vessel moves across the surface of a body of water, there is flow back past the vessel hull relative to the hull. For a vessel moving in still water, the flow approaches the vessel at a relative speed that is equal and opposite to the vessel speed. At the vessel bow, the flow velocity increases relative to the vessel and is deflected from a straight path by the oblique hull surface. A pressure gradient acting along the hull is required to cause this flow acceleration. The magnitude of the pressure gradient and total pressure change depend on the vessel speed, the hull surface geometry, and the channel cross-section shape if the channel is relatively shallow and/or narrow. If the vessel is moving in a confined channel, the flow acceleration and resulting pressure gradient will be greater than if the vessel is moving across a wide and deep water body.

For a common vessel hull shape, the pressure rises in the vicinity of the bow, then falls to below the free stream pressure over the midsection of the vessel, and rises again at the stern. The water surface profile along the hull responds to this pressure distribution, causing the surface to rise at the bow and stern and to fall along the midsection. The pressure gradient and water surface rise at the stern will usually be less than at the bow owing to flow separation at the rear section of the hull. If the stern of the vessel is square rather than tapered, the flow separation will be significant, and there will be a negligible pressure rise compared with that which occurs at a tapered stern.

When responding to the sharp pressure gradients at the bow and possibly at the stern, which induce a rapid rise and fall in the water surface, inertia causes the water surface to lag behind its equilibrium position and produces a surface oscillation. This, in turn, produces the pattern of free waves that propagate out from the vessel. Consequently, the hull pressure distribution and resulting height of waves generated by the vessel depend on the relative velocity of flow past the hull, the hull geometry, and the clearance between the hull and the channel side and bottom. The period and direction of propagation of the vessel-generated free waves depend only on the vessel speed and the water depth.

The pressure rise at the bow and stern and the pressure drop along the vessel midsection also cause vessel sinkage and trim. Sinkage and trim are particularly significant in confined channels where the resulting pressure variations are greater for a given vessel hull form and speed. In a relatively confined channel, the raised water levels at the bow and stern and the lowered water level along the midsection can extend to the channel bank and affect its stability.

Thus, for increasing vessel speed or for the same speed in increasingly confined channels, the generated wave heights would increase. The increase in generated wave heights occurs provided that the vessel does not plane. For some lighter vessels at higher speeds, the hydrodynamic forces on the hull lift the vessel (planing) so it "skims" the water surface. When a vessel planes, the wave heights are lower than they otherwise would be and do not noticeably increase with increasing vessel speed.

Wave Pattern and Characteristics, Deep Water

Figure 1 shows the resulting pattern of wave crests generated by the bow of a vessel moving in deep water. (Only the waves in the vicinity of the vessel are

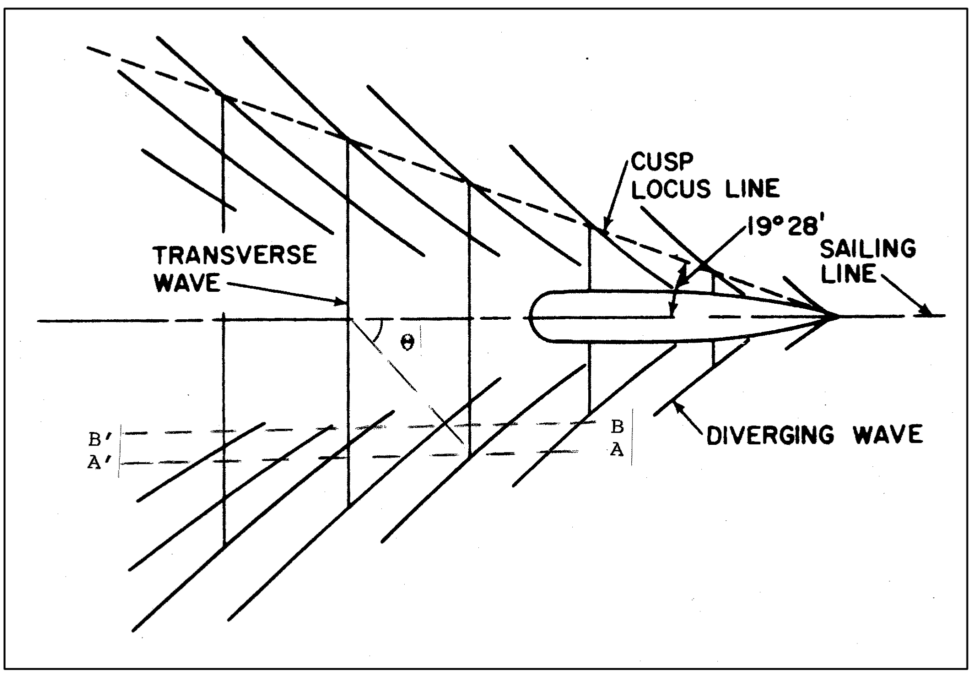

Figure 1. Deep water wave crest pattern by the bow of a moving vessel

shown. The pattern would spread out from the vessel with decreasing wave amplitudes until no longer noticeable.) The pattern consists of symmetrical sets of diverging waves that move obliquely out from the sailing line and a single set of transverse waves that move in the direction of the sailing line. The transverse and diverging waves meet to form cusps located along a pair of lines that form an angle of 19°28' with the sailing line. The highest waves in the pattern are found along this cusp locus line. If the vessel speed is increased, the lengths (and celerities) of the waves increase and the pattern spreads out but retains the same geometric shape. A similar pattern of waves, but typically with much lower amplitudes, would be generated at the vessel stern and superimposed on the pattern propagating out from the bow.

The wave pattern remains steady with respect to the vessel as the vessel travels at a speed V.[1] Thus the speed or celerity C of the waves is given by

$$C = V \cos\theta \qquad (1)$$

where θ is the angle between the sailing line and the direction of wave propagation (Figure 1). For the diverging waves in deep water, the theoretical value for θ is 35°16' (Thompson 1887). (This means that the angle the crest of the diverging wave makes with the sailing line at the cusp point is 180°- 90° - 35° 16' = 54°44' Figure 1.)

For successive waves out from the vessel bow, diffraction causes the length of both the diverging and transverse wave crests to increase. This decreases the wave energy density at any point on the wave and consequently decreases the wave height. Havelock (1908) analytically demonstrated that the wave heights at the cusp points should decrease at a rate that is inversely proportional to the cube root of the distance from the bow, while the transverse wave heights at the sailing line should decrease at a rate that is inversely proportional to the square root of the distance from the bow. Consequently, the diverging waves become relatively higher than the transverse waves at increasing distances from the bow of the vessel.

Figure 2 shows the wave record measured at three distances from the sailing line for a model cargo vessel sailing in deep water. Each record shows an initial height increase to a peak at the third or fourth wave and then a gradual decrease over the remainder of the record. A comparison of Figures 1 and 2 shows that the initial wave height increase to the peak and past the peak would be for the initial diverging waves measured at successively closer points to the cusp and beyond. The remainder of the record should be dominated by the transverse waves (Figure 1). Close inspection of the wave records shows a period of about 1.19 sec for the initial waves, which are diverging waves, shifting to a period of about 1.48 sec for the remaining waves, which are predominately transverse waves. The waves that might be generated at the stern of the vessel do not appear in the record.

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[1] For convenience, symbols and abbreviations are listed in the notation (Appendix B).

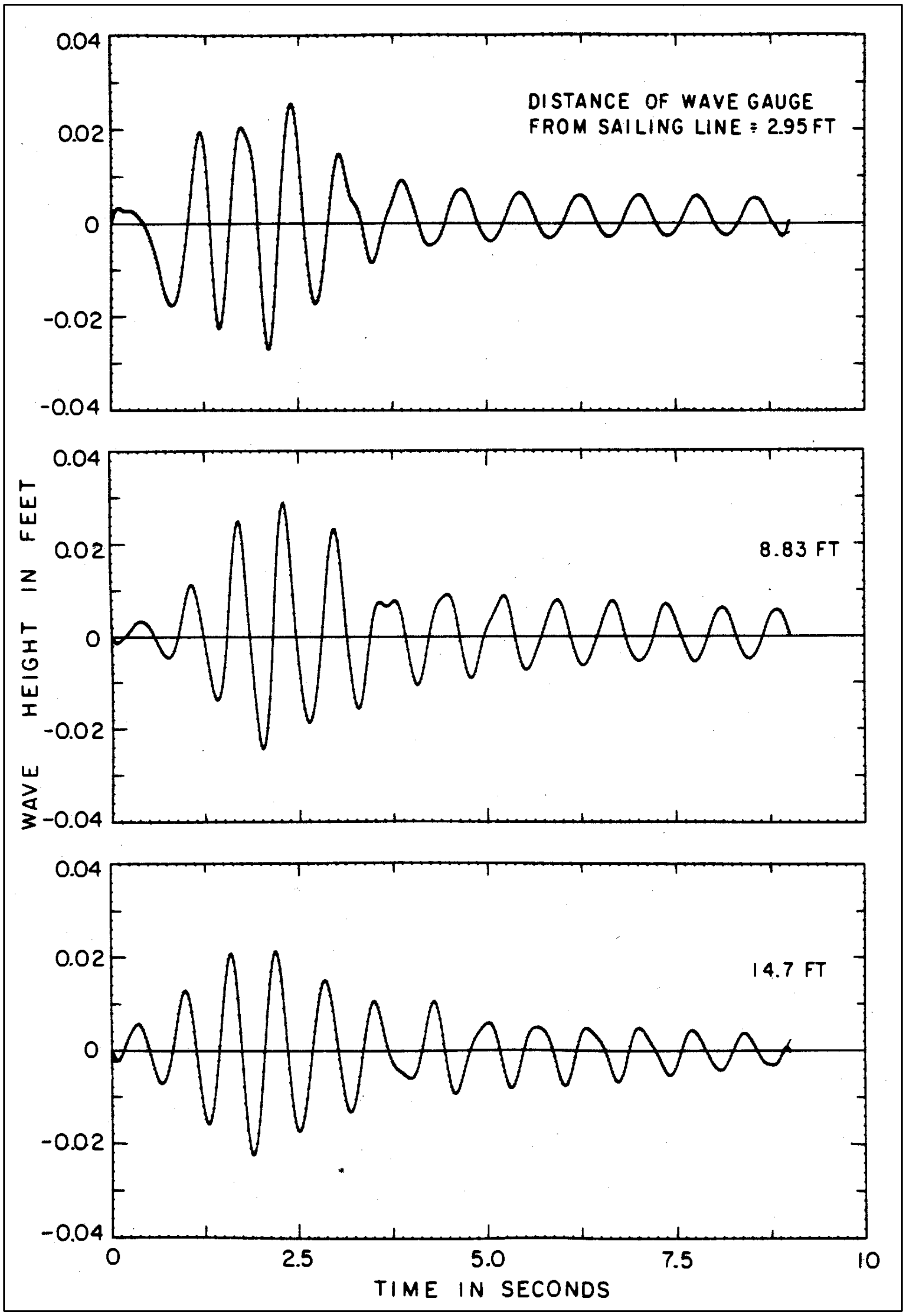

Figure 2. Wave record at three distances from the sailing line for a model cargo vessel in deep water (Das 1969)

Either they are too low to register or, more likely, the records are not sufficiently long to reach the point where they would appear.

A wave gauge located at point *A* would measure waves along line *A* - *A*' including measurement of the cusp point on the fourth diverging wave (Figure 1). A gauge located closer to the sailing line at *B* would measure waves along the line *B* - *B*' which would miss the cusp point. The records would be somewhat different with the gauge *A* record rising to more of a peak than the gauge *B* record, and the highest wave in record *A* possibly being higher than the highest wave in record *B* even though this record is measured closer to the sailing line.

Wave Pattern and Characteristics, Shallow Water

When a wave is propagating in water having a depth of less than approximately half the length of the wave, the wave-induced water particle motion reaches to the bottom and the water depth affects wave characteristics. The longer transverse waves would feel bottom first. This occurs (Sorensen 1973) when the Froude number *F*, defined as

$$F = \frac{V}{\sqrt{gd}} \tag{2}$$

(where *d* is the water depth below the still water line and *g* is the acceleration of gravity) reaches a value of 0.56. At a slightly lesser depth for a given vessel speed (i.e., greater *F*) the shorter diverging waves begin to interact with the bottom. Generally, when the Froude number is greater than 0.7 the vessel-generated wave system will begin to significantly respond to water depth effects, and noticeable changes in the wave system will occur. This condition is commonly referred to as shallow water.

As the Froude number increases from 0.7 to 1.0, several changes in the wave system will occur. Wave heights continue to rise at an increasing rate. Transverse wave heights increase at a faster rate than do diverging wave heights, so they become relatively more prominant as the Froude number approaches unity. This prominence is also greater for larger vessel drafts at a given vessel speed. The cusp locus angle increases from the deep water value of 19°28' to 90° at a Froude number of unity. This occurs because the angle that the diverging wave forms with the sailing line increases to 90°. (Consequently θ will decrease from 35°16' to zero degrees).

Figure 3 shows the water surface contours (measured by stereophotogrammetry) for one side of a model vessel moving at a speed that yields a Froude number of 0.85. Solid contour lines represent surface elevations above the still water level and dashed contour lines are below the still water level. Careful inspection shows the position of diverging and transverse waves meeting at the cusp locus line that extends obliquely back from the bow. Measurement of the

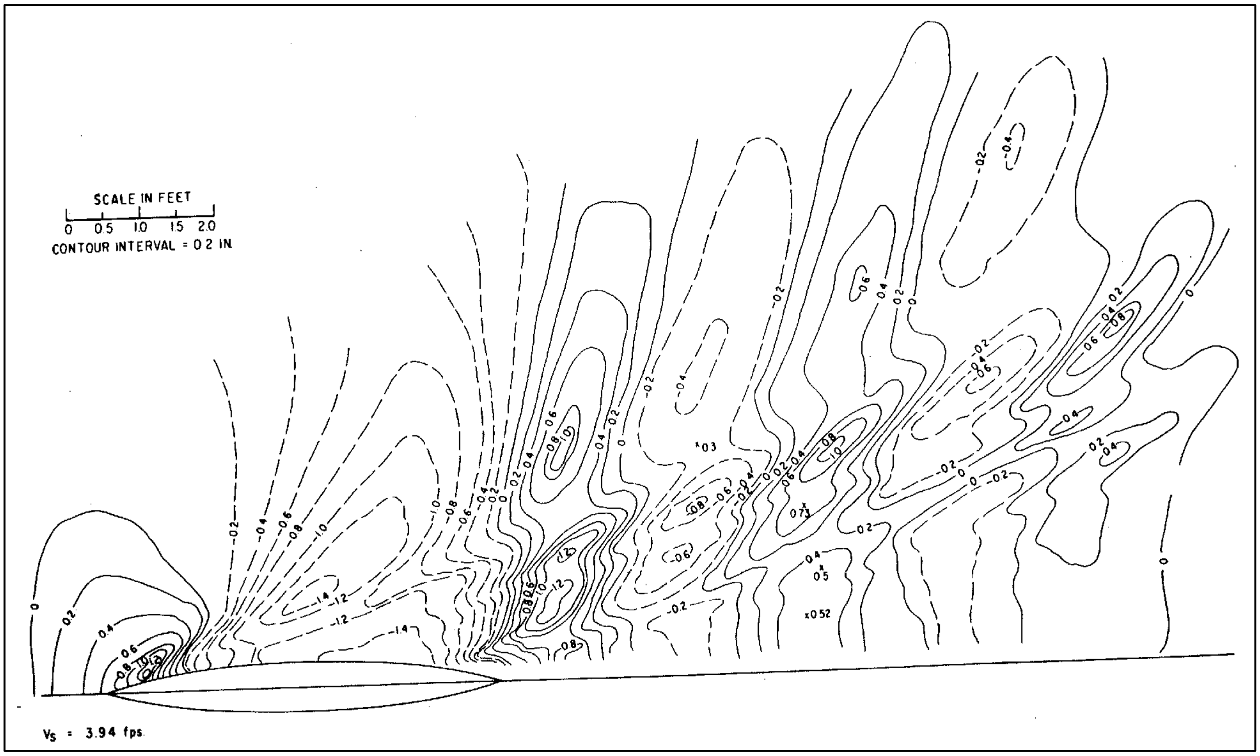

Figure 3. Measured water surface contours for the wave pattern generated by a model vessel, F = 0.85 (Sorensen 1966b)

cusp locus line angle with the sailing line yields a value of 26°. The two prominent diverging wave crests form angles of 73° and 71° respectively with the sailing line (compared to the theoretical deep water value of 54° 44').

At a Froude number of unity, when the cusp locus line angle is 90°, the transverse and diverging waves coalesce with their crests oriented perpendicular to the sailing line (at $F = 1.0$, $C = V = (gd)^{0.5}$). Also, as the Froude number approaches unity, the leading transverse and diverging waves are greatly accentuated at the expense of the following waves (because the wave group celerity approaches the wave phase celerity). Thus, at a Froude number of unity, essentially all of the wave energy is concentrated in the large leading wave that lies perpendicular to the sailing line near the bow, and the waves immediately behind this leading wave rapidly decrease in height.

For constricted channels and Froude numbers near unity, particularly when the wave crest axis is nearly perpendicular to the embankment, the bank will limit the extension of the wave along its axis by diffraction. Consequently, the wave height would be higher than it would be if the crest were free to extend to its natural length.

A wave propagating in water cannot have a celerity that exceeds the critical velocity (i.e., $(gd)^{0.5}$). So when the vessel's Froude number exceeds unity, transverse waves cannot exist. The resulting wave system consists of a series of straight diverging waves extending back from the bow with the leading wave forming an angle with the sailing line given by

$$a = \arcsin\left(\frac{1}{F}\right) \qquad F > 1 \tag{3}$$

For vessel speeds with $F > 1$ the wave heights are less than the peak height achieved at $F = 1$ and heights decrease as the vessel speed increases (Johnson 1958, Sorensen 1966b).

In constricted channels, self-propelled vessels that do not plane cannot attain velocities where $F > 1$. They are usually limited to a velocity defined approximately by $0.9F$ (Permanent International Association of Navigation Congresses 1987). If the vessel is moving at a velocity that yields a Froude number around 0.9, owing to the reduced clearance at the hull's wider midsection, the flow velocity at the midsection will be around the critical velocity. Increasing propeller speed will not make the vessel speed increase because the propellers cannot draw any additional flow past the vessel; therefore, the vessel speed is limited.

3 Predictive Models

Diverging Wave Direction

The dominant vessel-generated waves, as they travel out from the sailing line, are the diverging waves. They travel in the direction θ with respect to the vessel sailing line. As discussed θ varies from 35°16' for deep water to zero degrees for a Froude number of unity. Using these theoretical limits and the available experimental data, Weggel and Sorensen (1986) developed the empirical equation

$$\theta = 35.27\,(1 - e^{12(F-1)}) \qquad F < 1 \tag{4}$$

where θ is given in degrees and F has values between 0 and 1.0.

For Froude numbers in excess of unity, the direction of propagation of the vessel-generated waves can be determined from Equation 3 with θ = 90° - α.

Wave Period and Length

The celerity of the transverse waves is equal to the vessel speed. The celerity of the diverging waves can be determined from Equation 1 with θ determined from Equation 4 for a given vessel speed and water depth. Given the wave celerity, the length L and the period T of the transverse or diverging waves can be calculated from Equations 5 and 6, respectively.

$$C^2 = \frac{gL}{2\pi} \tanh \frac{2\pi d}{L} \tag{5}$$

$$T = \frac{L}{C} \tag{6}$$

Equation 5 can be solved by trial and error; then Equation 6 can be solved directly for the wave period.

Wave Height

The vessel-generated wave height is more difficult to predict. This is because it is dependent on more than the vessel speed and the water depth. Vessel-generated wave height is dependent on the bow geometry, the operating draft of the vessel, the distance from the sailing line, and in relatively confined channels, the clearance between the vessel hull and the channel bottom and sides. Also, the wave height varies throughout the wave pattern so one must define which wave height is being predicted. Most commonly the wave height reported for field and laboratory measurement programs and used for all height prediction models is the maximum wave height H_m from the wave record as depicted in Figure 4.

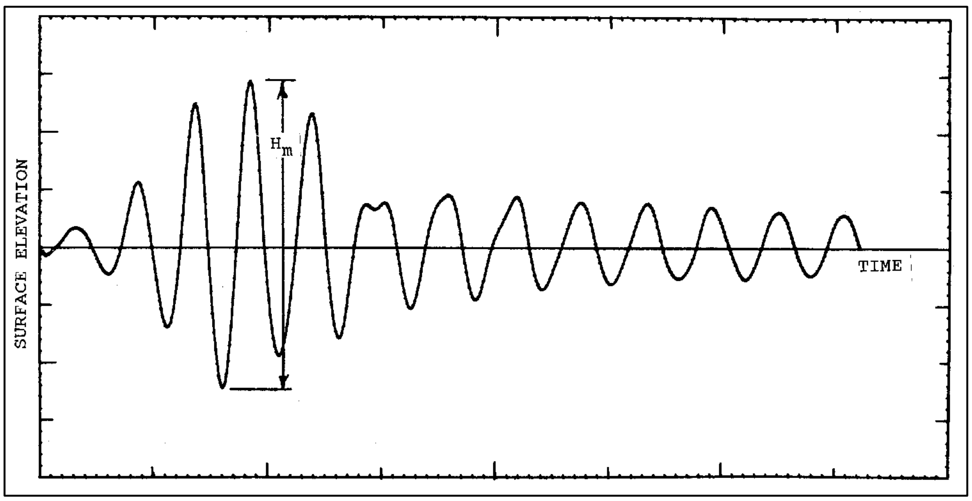

Figure 4. Typical vessel-generated wave record with H_m denoted

In a small number of studies the authors have defined an average or root mean square wave height from the wave record. This approach has a serious limitation in that the magnitude of the resulting wave height depends on the length of record being considered (Figure 4).

If the Froude number is greater than about 0.7 and/or the vessel draft to water depth ratio is large (approaching unity), the water depth will affect the resulting height of the wave being generated by a vessel. Wave height models should account for these effects. A separate, but possibly important, consideration is the possible additional change in wave height owing to depth effects as a wave propagates over an uneven bottom. That is, when the water depth to wave length ratio is less than a half, the wave height can be affected by refraction and shoaling effects. Refraction will also change the orientation of the wave crest. These effects can be reasonably estimated if the bottom hydrography is known, using standard wave analysis techniques.

One approach to predicting the wave height generated by a given vessel and operating condition is to search the literature of field and laboratory investigations for results from a similar vessel and operating condition. The following references contain measured vessel wave information that may be of use in making wave height predictions:

a. Bhowmik (1975).

b. Bhowmik, Demissie, and Guo (1982).

c. Bhowmik et al. (1991).

d. Bidde (1968).

e. Brebner, Helwig, and Carruthers (1966).

f. Das (1969).

g. Hay (1967).

h. Johnson (1958).

i. Kurata and Oda (1984).

j. Maynord and Oswalt (1986).

k. Nece, McCaslin, Christensen (1985).

l. Ofuya (1970).

m. Sorensen (1966a).

n. Sorensen (1966b).

o. Zabawa and Ostrom (1980).

An empirical equation or data plots may be provided in the above references, but measured data may not be tabulated, or only selected data are shown to demonstrate a point made in the paper.

Some authors have developed equations for the prediction of H_m as a function of dependent parameters such as vessel speed, distance from the sailing line, water depth, and simplified hull geometry parameters. These equations are typically regression analyses of data collected by the author with, in some instances, adjustment to satisfy some theoretical considerations. Most of the equations only employ the data set collected by the author and thus are limited to the vessel type and operational conditions that the author's data represent. These wave height prediction models are presented below

Model 1 (Balanin and Bykov)

Balanin and Bykov (1965) presented two equations based on Russian design practice that may be combined to yield an equation for the vessel wave height (presumably H_m) at the channel bank.

$$H_m = \frac{1.25\,V^2}{g}\left[1-\left(1-\left(4.2+S_c\right)^{-1/2}\right)\left(\frac{S_c-1}{S_c}\right)^2\right]\left[\frac{2+\sqrt{w/L_v}}{1+\sqrt{w/L_v}}\right] \tag{7}$$

S_c is the channel section coefficient which is the channel cross-section area divided by the wetted cross-section area of the vessel at midship, w is the channel width at the water surface, and L_v is the vessel length.

It appears that this equation is applicable only to navigation canals of fairly restricted width. The decrease in wave height with distance from the bow does not appear to follow anything like the theoretical inverse cube root relationship discussed above. It probably only applies to a fairly restricted class of vessels that were in use on the canals when the equation was developed.

Model 2 (U.S. Army Corps of Engineers)

An equation that is somewhat similar to but much simpler than Equation 7 was employed by the U.S. Army Corps of Engineers, Huntington District (1980) to predict bow diverging wave heights at the bank in navigation canals. This equation is

$$H_m = 0.0448\,V^2\left(\frac{D}{L_v}\right)^{1/2}\left(\frac{S_c}{S_c-1}\right)^{2.5} \tag{8}$$

where D is the vessel draft. Though this equation was applied on the Ohio River for commercial tows, the actual channel size and vessel used to develop the equation is unknown. It was most likely developed for a restricted channel since distance from the vessel is not employed.

Model 3 (Bhowmik)

Bhowmik (1975) presented the results of a small number of measurements of waves generated by a single vessel moving at three different speeds (7.6, 9.0, and 21.1 mph[1]) and three different distances from a wave gauge. The vessel was 18 ft long, and had a beam of 7.25 ft and a midship draft of 3.25 ft. It displaced about

[1] A table of factors for converting Non-SI units of measure to SI units is found on page vi.

2,200 lb, but no other details were given about the vessel. A regression analysis of the resulting data yielded the following relationship

$$\left(\frac{H_m}{D}\right)^2 = 0.0345\, V^{1.174} \left(\frac{x}{L_v}\right)^{-0.915} \tag{9}$$

where x is the distance from the vessel sailing line to the point of wave measurement and the vessel speed V is in miles per hour.

According to Equation 9, H_m is proportional to $V^{0.587}$ which is much lower than reported by most investigators who show increases to a power greater than unity (typically 2 or higher; e.g., see Equations 7, 8, 10, 15, and 16). One suspects that the vessel was operating normally at the two low speeds and planing at the high speed so that there was no significant change in wave height for the three speeds. H_m is proportional to $x^{-0.46}$ which approximates the theoretical value of -0.333. The water depth is not included in Equation 9 which implies that the equation would only be for deep water waves (i.e., F less than about 0.7). As mentioned above, the tests were only for one vessel with a hull type that is not specified.

Model 4 (Gates and Herbich)

Gates and Herbich (1977) presented a method for predicting the cusp wave height H_m generated by large vessels moving in deep water (i.e., $F < 0.7$). They start with an equation from Saunders (1957) which gives the wave height being generated at a vessel's bow H_b

$$H_b = \left(\frac{K_w B}{L_e}\right) \frac{V^2}{2g} \tag{10}$$

In Equation 10, B is the maximum beam width of the vessel hull and L_e is the entrance length of the hull defined as the distance along the sailing line from the bow stem back to the point where the parallel middle body begins. (This approach is aimed at large vessels such as cargo vessels and tankers which have a bow located fore of a long middle section having parallel sides. Basically, B/L_e is an indication of the bow angle at the water line.) K_w is a coefficient that Saunders (1957) plotted as a function of the ratio $V/(L_v)^{0.5}$ using data from larger vessels including tankers, liners, a seaplane tender, a gun boat, and a cruiser. This relationship is given in Figure 5 (Saunder's original figure modified by Gates and Herbich to fit experimental data). Since the horizontal scale in Figure 5 is not dimensionless, one must use English units to determine $V/(L_v)^{0.5}$. Using data from sixteen tanker and bulk cargo ships, Gates and Herbich (1977) presented an equation which may be used to estimate L_e for a given vessel length (Equation 11). The equation is

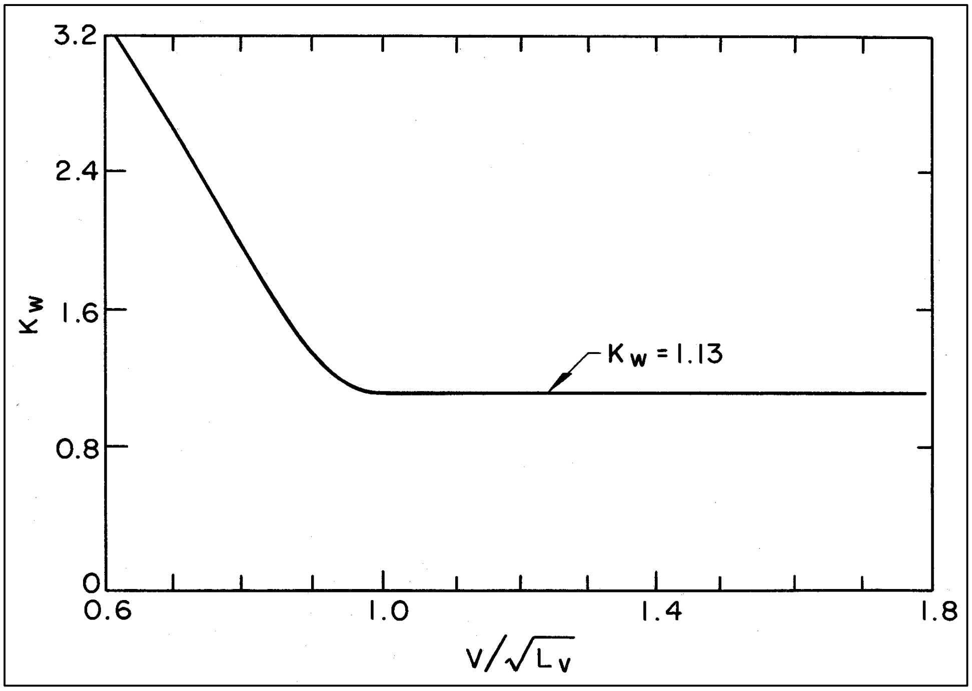

Figure 5. Proposed K_w values for the Gates and Herbich (1977) model

$$\frac{L_e}{L_v} = 0.417 - 0.00235\ L_v \tag{11}$$

To determine the wave height change as a function of distance from the bow, Gates and Herbich (1977) used the theoretical formulations of Havelock (1908) for wave height at the cusp points in deep water. Employing these equations, the distance to any cusp point is given by

$$x = \frac{1.21\,V^2\,(2N + 1.5)}{g} \tag{12}$$

where N = 1, 2, 3 . . . . for the successive cusp points out from the sailing line. Then H_m at these cusp points is given by

$$H_m = \frac{1.11\,H_b}{(2N + 1.5\,)^{0.33}} \tag{13}$$

Gates and Herbich (1977) checked their method against the waves measured by Brebner, Helwig, and Carruthers (1966) for two large vessels at one speed and three and five cusp point distances respectively from the sailing line. The results were quite satisfactory.

Model 5 (Bhowmik, Demissie, and Guo)

Bhowmik, Demissie, and Guo (1982) reported measured vessel wave data from 59 barge tows consisting of from 2 to 18 barges and a tugboat operating on the Illinois and Mississippi Rivers. Vessel group speeds varied from 3.2 to 20.3 ft/sec and wave gauge distances from the sailing line varied from 30 to 700 ft. Channel blockage ratios (reciprocal of S_c) varied from 14.7 to 226.9. Often individual groups of waves could be discerned from the barge tow bow and stern and from the tugboat driving the tow. The authors compared the measured maximum wave heights to those given in Equations 7 and 8, but with little success. They then tried a multivariate regression analysis between the measured wave heights and those parameters they felt were important to wave generation. The best result (correlation coefficient = 0.87) was

$$\frac{H_m}{D} = 0.133 \frac{V}{\sqrt{gD}} \tag{14}$$

Even though the range of vessel speeds was large and it is unlikely that any of the vessels were planing, there is a linear relationship between H_m and V. It does not include the wide range of distances between the sailing line and the point at which waves were measured.

Model 6 (Blaauw et al.)

Blaauw et al. (1984) present an equation that is based on Delft Hydraulics Laboratory field (canal) and laboratory measurements and employs a format similar to Gates and Herbich (1977). The height of the "interference peaks" (i.e., H_m) is given by

$$H_m = Ad \left(\frac{S}{d} \right)^{-0.33} F^{2.67} \tag{15}$$

where S is the distance (perpendicular to the sailing line) from the vessel's side to the point at which the wave height is being calculated (i.e., $S = x - B/2$) and A is a coefficient that depends on the vessel hull type and condition. Given values are: loaded pushing unit $A = 0.8$; empty pushing unit $A = 0.35$, and conventional inland motor vessel $A = 0.25$.

Model 7 (Permanent International Association of Navigation Congresses)

A Permanent International Association of Navigation Congresses (PIANC) working group report on the design of canal revetments (1987) contains an equation similar to Equation 15 for waves generated by vessels in inland waterways. This equation states that

$$H_m = A'' d \left(\frac{S}{d} \right)^{-0.33} F^4 \tag{16}$$

where the coefficient A'' has a value of unity.

A similar equation is presented in a paper by Verhey and Bogaerts (1989) where the fourth power for the Froude number and and the coefficient A'' are given based on laboratory and field tests in deep water (i.e., $F < 0.7$). The coefficient A'' has values of 1.0 for tugs, patrol boats, and loaded conventional inland motor boats (thus Equation 16), 0.5 for empty European barges, and 0.35 for empty conventional motor vessels.

Verhey and Bogaerts (1989) report that an attempt was made to incorporate the bow geometry of the ship in the coefficient A'' reported above. They give

$$A'' = \frac{KD}{L_e} \tag{17}$$

which uses D/L_e rather than B/L_e (as in Gates and Herbich 1977) to define the bow geometry. They do not give specific values for K but say it was determined for a range of vessel types (passenger ships, freighters, tankers, supply boats, ferries, and container ships) and ranged between 1.5 and 4.0. (Note from Equations 16 and 17 that this range of K values gives a commensurate range of H_m values.) In their investigations, values of L_e in many cases had to be estimated which led to variation in the results for K.

Model 8 (Sorensen and Weggel)

Sorensen and Weggel (1984) and Weggel and Sorensen (1986) developed a vessel wave height prediction model based on the measured laboratory and field data then available in the literature. They noted some of the important limitations on the available data as far as developing a completely satisfactory wave prediction model. They found that:

a. Usually the hull geometry was not well defined. At best the author gave the vessel length, beam, and draft (not always at the water line) and possibly the displacement.

b. Most vessels were operated only at low vessel draft to water depth ratios.

c. The only wave height information reported was H_m.

d. The range of vessel hull types for which wave data were reported was somewhat limited.

e. Vessels were operated over a limited range of Froude numbers.

Their initial model related H_m to the vessel speed, the distance from the sailing line, the water depth, and the vessel displacement volume *W*. This yielded four dimensionless variables:

$$F = \frac{V}{\sqrt{gd}} \qquad x^* = \frac{x}{W^{0.33}}$$
$$H_m^* = \frac{H_m}{W^{0.33}} \qquad d^* = \frac{d}{W^{0.33}} \tag{18}$$

The basic initial model, in terms of these dimensionless variables, is given by

$$H_m^* = \alpha\,(x^*)^n \tag{19}$$

where α and *n* are a function of the Froude number and dimensionless depth as follows:

$$n = \beta\,(d^*)^{\delta} \tag{20}$$

where

$$\beta = -0.225\,F^{-0.699} \qquad 0.2 < F < 0.55$$
$$\beta = -0.342 \qquad 0.55 < F < 0.8 \tag{21}$$

and

$$\delta = -0.118\,F^{-0.356} \qquad 0.2 < F < 0.55$$
$$\delta = -0.146 \qquad 0.55 < F < 0.8$$

$$\log\alpha = a + b\log(d^*) + c\log^2(d^*) \tag{22}$$

where

$$a = \frac{-0.6}{F}$$
$$b = 0.75\ F^{-1.125} \tag{23}$$
$$c = 2.653\ F - 1.95$$

Using Equations 19 through 23, H_m can be determined given the vessel speed, displacement, water depth, and distance from the sailing line. These equations are valid for vessel Froude numbers from 0.2 to 0.8, which are common for most vessel operations.

This model was subsequently improved by modifying the value of H_m^* calculated from Equation 19 (called $H_m^*(19)$) by the following relationship:

$$H_m^* = A'\ H_m^*(19) - B' \tag{24}$$

where A' and B' attempt to better include the effects of hull geometry. Table 1 is a tabulation of A' and B' values for vessel types used in the model development, where A' and B' are a function of the block coefficient, dimensionless length, dimensionless beam, and dimensionless draft defined as follows:

$$\textit{Block Coefficient} = \frac{W}{(\gamma_v LBD)}$$

$$\textit{Dimensionless Length} = \frac{L_v}{W^{1/3}}$$

$$\textit{Dimensionless Beam} = \frac{B}{W^{1/3}}$$

$$\textit{Dimensionless Draft} = \frac{D}{W^{1/3}}$$

where γ is the specific weight of water.

Model 9 (Bhowmik et al.)

Bhowmik et al. (1991) measured the waves generated by 12 different recreational type vessels (246 test runs) ranging in length from 3.7 to 14.3 m and draft from 0.1 to 0.76 m. Vessel speeds ranged from 3.2 to 20.3 m/sec. From a regression analysis of all of the data, they developed the following equation

$$H_m = 0.537\ V^{-0.346}\ x^{-0.345}\ L_v^{0.56}\ D^{0.355} \tag{25}$$

Table 1
Coefficients A′ and B′ for Weggel and Sorensen Model

Vessel Type	Investigator	Block Coefficient	Dimensionless Length	Dimensionless Beam	Dimensionless Draft	A′	B′
Prototype (various types)	Sorensen (1967)	Varies	Varies	Varies	Varies	1.00	0.000
Cruiser	Das (1969)	1.177	5.517	0.679	0.226	3.52	0.078
Box models	Sorensen (1966b)	0.897	4.313	0.719	0.359	2.60	0.063
Barge	Hay (1967)	0.861	4.726	0.977	0.251	1.53	0.005
Barge	Bidde (1968)	0.797	4.869	0.977	0.259	2.17	0.030
Moore dry dock tanker	Hay (1967)	0.691	5.834	0.764	0.324	2.55	0.036
Auxilary supply vessel	Hay (1967)	0.629	4.922	1.141	0.283	1.89	0.025
Mariner class cargo ship	Hay (1967)	0.526	6.357	0.831	0.270	0.84	0.007
Mariner class cargo ship	Bidde (1968)	0.526	6.357	0.831	0.270	0.91	0.010
Mariner class cargo ship	Das (1969)	0.526	6.357	0.831	0.270	0.73	0.008
Ferryboat	Kurata & Oda (1984)	0.514	5.343	0.949	0.384	3.19	0.179
Tugboat	Hay (1967)	0.475	4.670	1.050	0.429	1.73	0.015
Tugboat	Kurata & Oda (1984)	0.321	4.801	1.470	0.441	3.30	0.145

where metric units are to be employed in calculations.

The length and draft of the vessel are employed but no account is taken of the various hull forms (V-hull, johnboat, tri-hull, pontoon and cabin cruiser). The water depth is not included in the equation which would be reasonable for operational conditions where F < 0.7 (but for some of the test runs the depth Froude number significantly exceeded 0.7). The exponent of the term for the distance from the sailing line x (-0.345) is close to the theoretical value discussed in Havelock (1908). However, the exponent of the vessel speed term V (-0.346) indicates that the wave height is inversely and weakly proportional to the vessel speed. The logic of this is hard to understand.

Discussion of Predictive Models

The characteristics of a wave for a given water depth are completely defined by the wave height, period, and direction of propagation. For vessel waves, the wave period and direction (also the wave length and celerity) can be calculated from Equations 1, 3 or 4, 5, and 6. The wave period and direction are dependent only on the vessel speed and water depth and can be directly determined analytically. When the Froude number is less than about 0.7, $\theta = 35°16'$ and the following simplified relationships result:

$$C = 0.816\,V \tag{26}$$

$$L = \frac{2\pi\, C^2}{g} \tag{27}$$

$$T = \frac{2\pi C}{g} \tag{28}$$

As discussed above, prediction of the vessel-generated wave height is a much more complex undertaking. It depends on factors other than just the vessel speed and water depth. Thus, prediction of vessel-generated wave heights involves much more uncertainty. The nine wave height models presented above all yield a value for H_m, the maximum wave height in a wave record. Some authors employ the energy density of this peak wave which is simply $\gamma H_m^2/8$.

Any parameter that indicates the average wave height or the energy of the wave record will depend on the length of record being considered. Thus, any such value would be somewhat arbitrary and must be well defined when used. A typical wave record for a single vessel will consist of an initial group of high waves which contain a major portion of the wave energy. This is followed by significantly lower waves which progressively decrease in amplitude as the record extends. According to the linear wave theory, the energy E in a water wave for a unit width along the wave crest and for one wave length is given by

$$E = \frac{\gamma H^2 L}{8} \qquad (29)$$

The wave length for a given water depth depends only on the wave period (see Equations 5 and 6 or Equations 27 and 28 combined by eliminating C). Thus, for a typical vessel wave record where the wave period is relatively constant in the initial group of large waves, the energy content in each wave is dependent essentially on the wave height squared. Given this, perhaps the most logical way to derive a quantitative indication of vessel wave energy is to sum the energy in the waves that have a height higher than 10 percent of the maximum height (or 10 percent of the average of the highest two or three waves). This would yield a repetitive approach to evaluating wave records for energy content, and waves having less than 10 percent of the maximum wave height would have less than 1 percent of the energy of the maximum wave. This approach would also be reasonable for a vessel combination such as a multibarge tow which might generate several groups of high waves. The total energy in the group or groups would be the sum of the energies in each wave as indicated by Equation 30. Most commonly, for analysis of a wave record, an individual wave is designated by the portion of the wave record between two successive crossings of the water surface upward through the still water line (known as the zero-upcrossing method).

It is hard to compare the nine wave height prediction models in a directly quantitative way. Qualitatively, some of the models (i.e., 1, 2, and 5) neglect wave height decay with distance from the sailing line, a factor of importance in all cases except for narrow canals. Some of the models (i.e., 1, 2, 3, 5, and 9) do not consider variations in hull geometry in any way and model 6 in only a limited way. Some models (i.e., 3, 5, and 9) have an apparently incorrect relationship between vessel speed and maximum wave height. Only three models (i.e., 4, 7, and 8) pass this qualitative evaluation, and they have limitations for general use.

The Gates and Herbich (1977) model was developed for large seagoing vessels and a Froude number less than around 0.7. It could be improved for general use by the definition of K_w and L_e for additional vessels. The wave height is a function of the vessel speed squared. Perhaps some other power of the velocity head might produce a better empirical fit to experimental data.

A formulation like Equation 16 would be useful if either *A*" were provided for more vessel types or sufficient data were available to develop the *K* value in Equation 17.

The Weggel and Sorensen (1986) model is the most general in including all of the dependent factors. Even though it attempts to include vessel hull form, it does so in a somewhat indirect and limited way. Perhaps the coefficients *A*' and *B*' could be better formulated and more directly related to specific bow geometry parameters, given sufficient bow geometry data and related field data on generated wave heights.

Wave Height Model Evaluation

The best way to evaluate these models is to compare them to measured data. The data sets used for this comparison must satisfy three criteria:

a. They must not be data sets that were used to develop the model since all models contain a large element of empirical calibration or involve direct regression fitting of empirical data.

b. There must be sufficient information available, particularly on the vessel hull characteristics, to apply the model. The requirements of each model vary as to what information is required.

c. The experimental data should be for vessels having hull shapes somewhat similar to the recreational vessels that commonly operate on the Upper Mississippi River System.

As discussed above, the three models that are worthy of evaluation are those of Gates and Herbich (1977), PIANC(1987)/Verhey and Bogaerts(1989), and Weggel and Sorensen (1986). This evaluation follows.

Zabawa and Ostrum (1980) collected field data for a 26-foot-long cruiser having a deep V-hull. The vessel sailing lines were located 200 ft, 150 ft, and 100 ft from a wave gauge. The water depths at the three sailing lines were 13 ft, 12 ft, and 10 ft respectively, but the water depth at the gauge was only 2.2 ft. For the range of vessel wave periods (1.4 to 3.3 sec), calculations using linear wave theory indicate that wave shoaling would vary the wave height by about $\pm$ 7 percent between the generation point on the sailing line and the wave gauge. This does not include possible effects of wave refraction as the waves propagate over an uneven bottom to the wave gauge. The neighboring bottom hydrography was not given, so possible refraction effects could not be evaluated.

The general shape of the hull and the vessel length were the only information given on the vessel (beam, draft, and displacement were not given). Thus, only the PIANC(1987)/Verhey and Bogaerts(1989) method could be compared with the data. Also, many of the data runs were for vessel speeds that produced depth Froude numbers in excess of unity. Figure 6 shows a plot of the usable experimental data for the travel distances of 100, 150, and 200 ft. The data scatter widely showing a general trend of wave height increase with increasing vessel speed. The decrease in wave height with distance from the sailing line is not well defined. Also shown on Figure 6 are the predicted wave heights for travel distances of 100 and 200 ft using $A'' = 1.00$ (see Equation 16 where d is taken as the water depth at the sailing line).

Considering the scatter of the data, the PIANC(1987)/Verhey and Bogaerts (1989) procedure does reasonably well at matching the data. However, close inspection of Figure 6 suggests that the increase in wave height with increase in vessel speed might be too sharp. For example, Equation 16 has the maximum

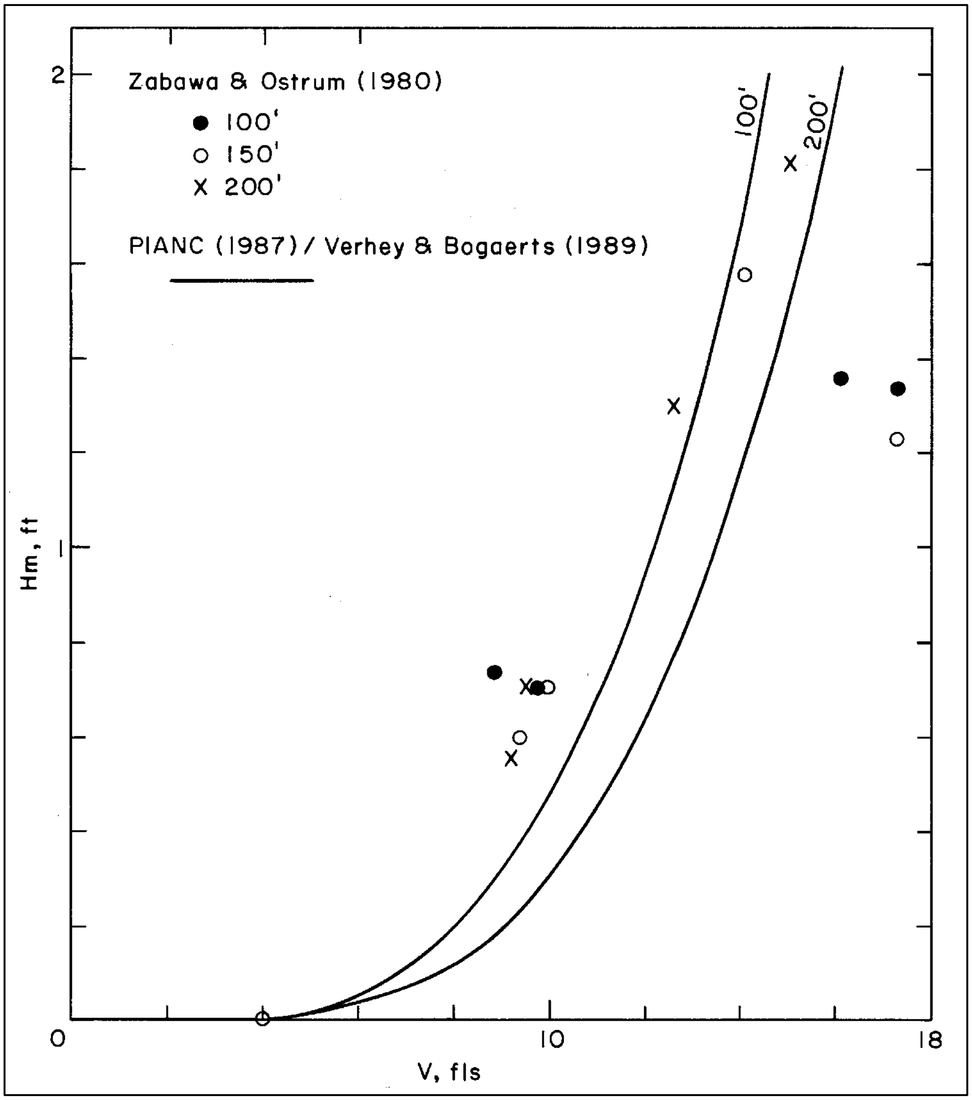

Figure 6. Zabawa and Ostrum (1980) field data compared with predicted results from the PIANC (1987)/Verhey and Bogaerts (1989) model

wave height increase as a function of vessel speed raised to the fourth power, whereas a lower power of vessel speed might be more appropriate.

Ofuya (1970) measured the waves generated by a 25-ft-long cruiser having a beam of 10 ft, a draft of 1.42 ft, and a displacement of 2.5 tons. The wave gauge was in water 25 ft deep, and the vessel sailing lines were 40, 150, 250, and 800 ft from the wave gauge where the water depths were 27, 30, 31, and 33 ft, respectively. For these water depths and typical vessel-generated wave periods, shoaling and refraction effects should not be a problem. The Ofuya (1970) data are plotted in Figure 7. There is the expected trend of increasing wave height with increasing vessel speed as well as a general trend of decreasing wave height with distance from the sailing line, but a fair amount of scatter is also present in the data.

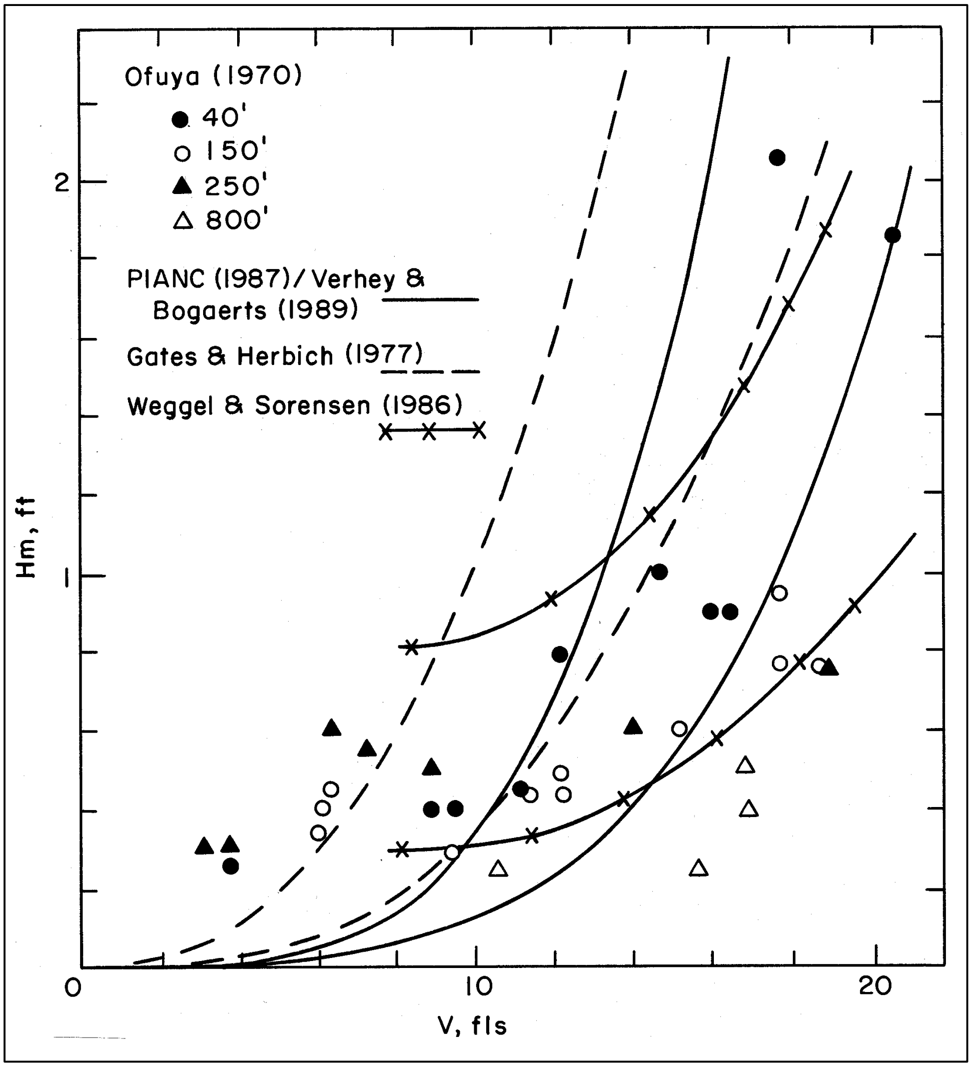

Figure 7. Ofuya (1970) field data compared with predicted results from the PIANC (1987)/Verhey and Bogaerts (1989), Gates and Herbich (1977), and Weggel and Sorensen (1986) models

Sufficient data are given on the vessel hull to apply all three of the models that are being evaluated. The results of these three models are shown in Figure 7 for wave travel distances of 40 and 800 ft which bracket the experimental distances. For the PIANC(1987)/Verhey and Bogaerts(1989) model, the value A'' = 1.0 was again used. For the Gates and Herbich (1977) model and a vessel length of 25 ft, Equation 11 was used to calculate L_e = 8.95 ft which appears to be reasonable. The value of K_w was determined to be 1.13 from Figure 5. The values of H_m were calculated at the cusp points closest to 40 ft and 800 ft, and interpolated values for 40 ft and 800 ft were determined (where cusps might not actually be located). For Weggel and Sorensen (1986), A' = 1.0 and B' = 0 were used. (Values of A' = 3.52 and B' = 0.78, which are based on the Das (1969) laboratory data for a cruiser, were also tried but gave predicted wave heights that were much too high for a given vessel speed.)

Inspection of Figure 7 indicates that none of the models match the experimental data over the full range of vessel speeds. The Gates and Herbich (1977) model underpredicts wave heights at the lower speeds and overpredicts heights at the higher speeds. A similar assessment can be made of the PIANC(1987)/Verhey and Bogaerts (1989) model, which more extremely underpredicts wave heights at low speeds but less extremely overpredicts heights at the higher speeds. The latter model may be the preferred of the two as there is usually more interest in the higher vessel speeds for design conditions. But, again, the fact that the wave height is a function of the vessel speed to the fourth power in this model does not seem to fit very well the trend of the data at the higher speeds. Particularly at the higher speeds, the best fit to the data appears to be the curves generated by the Weggel and Sorensen (1986) model. This model overpredicts wave heights at the very low speeds. (And, it produces the anomolous result of not extrapolating to zero height at zero speed.) Adjustment of the A' and B' values for this model could somewhat improve its fit to the data.

4 Upper Mississippi River System Applications

The objective of this investigation was to present the best model for vessel wave prediction with an emphasis on the common types of recreational vessels that operate on the Upper Mississippi River System (UMRS). From the limited evaluation presented in the previous section, it appears that the Weggel and Sorensen (1986) model gave the best available predictions for H_m (wave direction and period can be predicted by Equations 4 through 6). The Weggel and Sorensen (1986) model involves cumbersome calculations to determine H_m given the vessel type (A' and B'), displacement, and speed as well as the water depth and the distance from the sailing line. But, Weggel and Sorensen have used this model (with $A' = 1.0$ and $B' = 0$) on a few occasions for vessel wave height predictions for coastal design.

5 Summary and Recommendations

This report reviews the models available for vessel-generated wave prediction. Most of the models have limited application. The limited data available to evaluate these models show significant scatter and are deficient in the available supporting information on vessel hull characteristics.

A set of field experiments would be very useful in further evaluating the models presented herein and in improving their predictive capabilities for a given vessel hull form and operating draft. The experiments should be conducted with selected vessel hulls that are representative of common vessels used for recreation. The vessels should be ballasted so that they do not plane at higher speeds and the hull geometries and operating drafts should be well defined. The water body where the experiments are conducted should have a depth that yields a satisfactory range of Froude numbers for the vessel speeds employed, and the water depths over the range of wave propagation should be relatively constant to eliminate shoaling and refraction effects. Wave records should be taken for a sufficient range of vessel speeds and wave decay distances. Besides a value for H_m from each record, the wave energy in each record should be determined as discussed above. The simplest model to use is the PIANC (1987)/Verhey and Bogaerts (1989) model. The data from the recommended field experiments should be used to further develop the coefficients A'' and K for the vessels studied. The experimental data may also redefine the power to which the Froude number is raised. The data should also be used to improve the definition of the coefficients A' and B' in the Weggel and Sorensen (1986) model. Ideally, these coefficients should be related to vessel bow geometry.

References

Balanin, V. V., and Bykov, L. S. (1965). "Selection of leading dimensions of navigation canal sections and modern methods of bank protection." Sections 1-4, *21st Congress Proceedings*, Permanent International Association of Navigation Congresses, Stockholm.

Bhowmik, N. G. (1975). "Boat-generated waves in lakes" Technical Note, *Journal of the Hydraulics Division*, American Society of Civil Engineers, November, 1465-68.

Bhowmik, N. G., Demissie, M., and Guo, C.-Y. (1982). "Waves generated by river traffic and wind on the Illinois and Mississippi Rivers" Report UILI-WRC-82-167, Illinois State Water Survey, Champaign, IL.

Bhowmik, N. G., Soong, T. W., Reichelt, W. F., and Seddik, N. M. L. (1991). "Waves generated by recreational traffic on the Upper Mississippi River system," Research Report 117, Department of Energy and Natural Resources, Illinois State Water Survey, Champaign, IL.

Bidde, D. D. (1968). "Ship waves in shoaling water," Report HEL-12-6, Hydraulic Engineering Laboratory, University of California, Berkeley, CA.

Blaauw, H. G., de Groot, M. T., Knaap, F. C. M., and Pilarczyk, K. W. (1985). "Design of bank protection of inland navigation fairways." *Proceedings of the Conference on Flexible Armoured Revetments Incorporating Geotextiles*, London, 29-30 March 1984. Thomas Telford, 39-66.

Brebner, A., Helwig, P. C., and Carruthers, J. (1966). "Waves produced by ocean-going vessels: A laboratory and field study." *Proceedings of the 10th Conference on Coastal Engineering*, Tokyo. American Society of Civil Engineers, 455-65.

Das, M. M. (1969). "Relative effect of waves generated by large ships and small boats in restricted waterways," Report HEL-12-9, Hydraulic Engineering Laboratory, University of California, Berkeley, CA.

Gates, E. T., and Herbich, J. B. (1977). "Mathematical model to predict the behavior of deep-draft vessels in restricted waterways," Report TAMU-SG-77-206, Texas A&M University, College Station, TX.

Havelock, T. H. (1908). "The propagation of groups of waves in dispersive media, with application to waves on water produced by a travelling disturbance." *Proceedings of the Royal Society of London*. Series A, 81, 398-430.

Hay, D. (1967). "Ship waves in navigable waterways," Report HEL-12-5, Hydraulic Engineering Laboratory, University of California, Berkeley, CA.

Johnson, J. W. (1958). "Ship waves in navigation channels." *Proceedings of the 6th Conference on Coastal Engineering*, Gainesville, FL. Council on Wave Research, Berkeley, CA, 666-90.

Kurata, K., and Oda, K. (1984). "Ship waves in shallow water and their effects on moored small vessel." *Proceedings of the 19th Conference on Coastal Engineering*, Houston, TX. American Society of Civil Engineers, 3257-73.

Maynord, S. T., and Oswalt, N. R. (1986). "Riprap stability and navigation tests for the divide-cut section Tennessee-Tombigbee Waterway - hydraulic model investigation," Technical Report HL-86-3, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

Moffit, F. H. (1968). "Mapping of ship waves breaking on a beach," Report HEL-12-8, Hydraulic Engineering Laboratory, University of California, Berkeley, CA.

Nece, R. E., McCaslin, M. R., and Christensen, D. R. (1985). "Ferry wake study," Final Report, Project Y-2811, Task 16, Washington State Transportation Center, University of Washington, Seattle, WA.

Ofuya, A. O. (1970). "Shore erosion - ship & wind waves: St. Clair, Detroit & St. Lawrence Rivers," Report 21, Marine Engineering Division, Department of Public Works, Canada.

Permanent International Association of Navigation Congresses. (1987). "Guidelines for the design and construction of flexible revetments incorporating geotextiles for inland waterways," Working Group 4 of the Permanent Technical Committee, Brussels.

Saunders, H. E. (1957). *Hydrodynamics in Ship Design*, vol 2, Society of Naval Architects and Marine Engineers, New York.

Sorensen, R. M. (1966a). "Investigation of ship-generated waves," Report HEL-12-1, Hydraulic Engineering Laboratory, University of California, Berkeley, CA.

Sorensen, R. M. (1966b). "Ship waves," Report HEL-12-2, Hydraulic Engineering Laboratory, University of California, Berkeley, CA.

Sorensen, R. M. (1973). "Ship-generated waves." *Advances in Hydroscience*, Academic Press, New York, 9, 49-83.

Sorensen, R. M., and Weggel, J. R. (1984). "Development of ship wave design information." *Proceedings of the 19th Conference on Coastal Engineering*, Houston, TX, 3-7 September 1984. Billy L. Edge, ed., American Society of Civil Engineers, New York, III, 3227-43.

Thompson, W. (Lord Kelvin). (1887). "On the waves produced by a single impulse in water of any depth, or in a dispersive medium." *Proceedings of the Royal Society of London*. Series A, 42, 80-85.

__________. "On ship waves." *Proceedings of the Institute of Mechanical Engineers*, London. 409-33.

U.S. Army Corps of Engineers, Huntington District. (1980). "Gallipolis locks and dam replacement, Ohio River, phase I - advanced engineering and design study," General Design Memorandum, Huntington, WV.

Verhey, H. J., and Bogaerts, M. P. (1989). "Ship waves and the stability of armour layers protecting slopes." *Proceedings of the 9th International Harbor Congress*, Antwerp, Belgium.

Weggel, J. R., and Sorensen, R. M. (1986). "Ship wave prediction for port and channel design." *Proceedings of the Ports '86 Conference*, Oakland, CA, 19-21 May 1986. Paul H. Sorensen, ed., American Society of Civil Engineers, New York, 797-814.

Zabawa, C., and Ostrom, C. (1980). "The role of boat wakes in shore erosion (in Anne Arundel County, Maryland)," Final Report, Coastal Resources Division, Maryland Department of Natural Resources, Annapolis, MD.

Appendix A
Annotated Bibliography

This bibliography is a survey of the literature on the waves generated by a moving vessel. Specifically, the focus is on those references that contain useful material on vessel wave theory and analytical prediction, empirical procedures for vessel wave prediction, field and laboratory vessel wave measurement programs, or vessel wave analysis for coastal/hydraulic engineering design applications (e.g., prediction of bank erosion, shoreline stabilization, and marina design).

Balanin, V. V., and Bykov, L. S. (1965). "Selection of leading dimensions of navigation canal sections and modern methods of bank protection." Sections 1-4, *21st Congress Proceedings*, Permanent International Association of Navigation Congresses, Stockholm.

The authors give a pair of equations for the prediction of vessel-generated wave height that have been used in the old USSR, but for which no further reference is provided. The wave height at the channel bank is given in terms of the vessel speed, the channel width at the water surface, the vessel length, and the channel section coefficient, which is defined as the channel cross-section area divided by the submerged midship cross-section area of the vessel.

Bhowmik, N. G. (1975). "Boat-generated waves in lakes," Technical Note, *Journal of the Hydraulics Division*, American Society of Civil Engineers, November, 1465-68.

This technical note presents the analysis of vessel wave data measured for a single small boat (18.5 ft long) passing a wave gauge at various speeds and distances from the gauge. The water was sufficiently deep, so shallow water waves were not generated. Results are plotted to yield an empirical equation relating the maximum wave height to vessel draft ratio to the vessel speed and to the distance from the sailing line to boat length ratio. (Selected wave data from the model studies by Das (1969) were also included in the plot used to develop the empirical equation.)

Bhowmik, N. G., Demissie, M., and Guo, C. -Y. (1982). "Waves generated by river traffic and wind on the Illinois and Mississippi Rivers," Report UILI-WRC-82-167, Illinois State Water Survey, Champaign, IL.

The authors measured the waves generated by vessels on selected sections of the Illinois and Mississippi Rivers. River flow velocities were measured so the correct vessel speed relative to the water could be established. The 59 test runs were all for barge tows consisting of from 2 to 18 barges and a tugboat. Reported data included the tow speed, number of barges, length, the component barge width and draft, the distance from the sailing line to the wave gauge, and the resulting maximum wave height measured. The authors attempted to correlate the maximum wave height to the other pertinent variables (channel water depth did not significantly vary, and barge bow geometries were all the same, i.e., square in planform). The resulting empirical equation related the wave height to vessel draft ratio to a Froude number based on the vessel draft. The distance from the sailing line did not enter the equation nor did the tow length or barge width. (The first barge probably has the largest pressure disturbance so additional barges would not likely generate higher waves; for square barges of relatively shallow draft, most of the return flow is under the barge except near the sides, so barge width would not be significant.)

Bhowmik, N. G., Soong, T. W., Reichelt, W. F., and Seddik, N. M. L. (1991). "Waves generated by recreational traffic on the Upper Mississippi River system," Research Report 117, Department of Energy and Natural Resources, Illinois State Water Survey, Champaign, IL.

Measurements were made of the waves generated by 12 different recreational craft at sites in the Illinois and Mississippi Rivers. The vessels ranged in length from 3.7 to 14.3 m and included a flat bottom johnboat, a pontoon, a tri-hull, and a variety of V-hulls. The 14.3-m-long cabin cruiser had the maximum draft of 0.76 m. There were 246 test runs with a pair of wave gauges set at each of four distances from the sailing line. Data on the vessel types and lengths and the water depths at the four gauge locations were tabulated, but the resulting measured wave data for the tests are not presented. The results are presented in terms of an empirical equation relating the vessel-generated maximum wave height as a function of the vessel speed, draft, length, and the distance from the sailing line. Of note is the result that the maximum wave height decreases as a function of distance from the sailing line to the -0.345 power. This is very close to theoretical (see Havelock (1908)) value of -0.333. However, even though vessel speeds for many of the tests resulted in depth Froude numbers greater than 0.7 (many exceeded 1.0), the water depth was not found to be significant in the regression analysis to develop the empirical equation. At these high speeds many of the vessels must have been planing which might have obscured the effect of water depth.

Bidde, D. D. (1968). "Ship waves in shoaling water," Report HEL-12-6, Hydraulic Engineering Laboratory, University of California, Berkeley, CA.

Model studies were conducted to measure the waves generated by two vessels, a Mariner Class cargo ship and a barge. Wave measurements were made at three points along a line to each side of the vessel, one side having a constant water depth and the other a constant water depth followed by a sloping beach (1:5, 1:10, and slope with a berm). Different vessel speeds and water depths (depth Froude numbers up to 0.85) were investigated. Results are plotted as the maximum wave height to water depth ratio versus depth Froude number for each of the six wave gauge positions.

Blaauw, H. G., de Groot, M. T., Knaap, F. C. M., and Pilarczyk, K. W. (1984). "Design of bank protection of inland navigation fairways." *Proceedings of the Conference on Flexible Armoured Revetments Incorporating Geotextiles*, London, 29-30 March 1984. Thomas Telford, 239-66.

The authors give an equation, based on Delft Hydraulics Laboratory experiments, for predicting the vessel-generated cusp point wave height at the bank of a canal. The wave height is given as a function of the vessel speed, the water depth, the distance from the vessel side to the canal bank, and a coefficient that depends on the vessel hull form. Values of the coefficient for a loaded pushing unit, empty pushing unit, tugboat, and conventional inland motor vessel are given.

Brebner, A., Helwig, P. C., and Carruthers, J. (1966). "Waves produced by ocean-going vessels: A laboratory and field study." *Proceedings of the 10th Conference on Coastal Engineering*, Tokyo. American Society of Civil Engineers, 455-65.

Data are reported for measurements of waves generated by three models of ocean-going vessels. The wave height is plotted versus vessel speed for different distances from the sailing line at each of two water depths. The authors introduce two parameters for defining the vessel hull characteristics that are significant to vessel wave generation. One is a fineness ratio defined as the length of the curved part of the bow divided by the square root of the hull cross-section area at the midsection. The other is a wave-making breadth defined as the same cross-section area divided by the curved length. They plot the wave height divided by the square root of the midsection cross-section area versus the fineness ratio and the vessel speed divided by the square root of the wave-making breadth. The data on which the resulting curves are based is not given in the plots but the authors state that the fineness ratio and wave-making breadth are reliable terms for defining the effects of vessel hull geometry.

Das, M. M. (1969). "Relative effect of waves generated by large ships and small boats in restricted waterways," Report HEL-12-9, Hydraulic Engineering Laboratory, University of California, Berkeley, CA.

Measurements were made of the waves generated by two model vessels (a cargo vessel and a cruiser) operated at a range of speeds at a deep (cargo vessel) and a shallow (both vessels) water depth. The measurements were made by four wave gauges located along a line perpendicular to the vessel sailing line. Fourier analyses were conducted on the wave records for each run to determine the energy density spectrum.

Data from Sorensen (1966a), who measured the waves generated by a geometrically similar series of five vessels of increasing size to study scale effects, were also analyzed. The energy density of the maximum wave height at each gauge location for Sorensen's data and the data from the cargo vessel and cruiser were plotted as a function of the vessel Froude number and as a function of distance from the sailing line. Miscellaneous other data plots for these data sets are also given.

Das, M. M., and Johnson, J. W. (1970). "Waves generated by large ships and small boats." *Proceedings of the 12th Conference on Coastal Engineering*, Washington, D.C. American Society of Civil Engineers, 2281-86.

This is a summary paper of the above report (Das 1969) and only presents the data collected by Das for the cargo vessel and cruiser.

Gates, E. T., and Herbich, J. B. (1977). "Mathematical model to predict the behavior of deep-draft vessels in restricted waterways," Report TAMU-SG-77-206, Texas A&M University, College Station, TX.

The aim of this study is to develop a multi-component math model for predicting vessel squat, bank suction forces and moments on a vessel and the necessary response to counteract these forces, vessel stopping distances, and the height of vessel-generated waves.

The starting point for a vessel wave height prediction model is the semi-empirical equation from Saunders (1957) that gives the wave height at the vessel bow in deep water as a function of the vessel speed, the ship bow geometry (ship beam divided by entrance length), and a coefficient dependent on the vessel class. An empirical equation is given for the entrance length. The wave height decay at any cusp point located out from the vessel bow is based on theoretical equations developed by Havelock (1908) which indicate that cusp height decrease is proportional to the cube root of the distance from the sailing line. Predicted wave heights using this model compared reasonably well with the heights measured by Brebner, Helwig, and Carruthers (1966) for two large vessels in the St. Lawrence Seaway. This method may be less suited for recreational craft and is not applicable to other than deep water.

Havelock, T. H. (1908). "The propagation of groups of waves in dispersive media, with application to waves on water produced by a travelling disturbance." *Proceedings of the Royal Society of London*. Series A, 81, 398-430.

Considering the pattern of waves generated by a circular pressure disturbance, Havelock derived the wave crest amplitude pattern for deep water transverse and diverging waves as a function of disturbance speed and position in the pattern. He found that the diverging wave cusp heights and the transverse wave crest heights at the sailing line will decrease at a rate inversely proportional to the cube root and square root, respectively, of the distances from the disturbance. The pressure field at the bow of a vessel would differ from that assumed by Havelock, so his equations would not likely be good for predicting actual wave heights; however they may be good for predicting the rate of decay of the wave components once they are generated.

Employing an approach similar to Thompson (1887) but for shallow water conditions Havelock also derived equations to define the diverging and transverse wave crest patterns for subcritical and supercritical disturbance speeds (i.e., Froude numbers less than and greater than 1).

Hay, D. (1967). “Ship waves in navigable waterways,” Report HEL-12-5, Hydraulic Engineering Laboratory, University of California, Berkeley, CA.

The waves generated by six model vessels were measured at four points along a line normal to the vessel sailing line for a range of vessel speeds (typical Froude numbers up to 0.7 to 0.8) and selected water depths. The six vessels included a cargo ship, a tanker, an auxiliary supply vessel, a barge, and a tug or fishing boat. Water depth to vessel draft ratios for each vessel were 1.375 to 3.5. The reported wave height at each gauge location is the maximum wave height in the wave record.

Hay, D. (1968). “Ship waves in navigable waterways.” *Proceedings of the 11th Conference on Coastal Engineering,* London. American Society of Civil Engineers, 1472-87.

This is a summary paper of the above report (Hay 1967) which gives more detail. In this conference paper, results are scaled to prototype conditions while in the lab report results are given in nondimensional form.

Hovgaard, W. (1909). “Diverging Waves,” Transactions of the Royal Institution of Naval Architects, London, 51, 251-61.

The author made observations of the diverging waves generated by a range of model and prototype vessels operating at different deep water speeds. Results included the angle of the diverging wave crests and cusp locus line with the sailing line and (for the prototype vessels) the height of the wave at the vessel bow.

Johnson, J. W. (1958). “Ship waves in navigation channels.” *Proceedings of the 6th Conference on Coastal Engineering,* Gainesville, FL. Council on Wave Research, Berkeley, CA, 666-90.

Six vessel models (one having both a large and small displacement) were towed at a range of speeds for one or two water depths and the water surface time histories were recorded at five locations along a line normal to the sailing line. Data on each vessel hull included the length, beam, draft, and displaced volume. The models included a small power boat (two displacements), a canoe, a barge, and three idealized hulls consisting of a rectangle with a triangular bow as a hull plan form. Results are presented in various forms including maximum wave height and crest elevation above the still water line versus vessel speed and distance from the still water line; period of the maximum wave versus depth Froude number; and maximum wave height/vessel draft ratio versus water depth/vessel draft and distance from the sailing line/ship length ratios.

A few field tests were also conducted on a 42-ft-long power boat. Eleven measurements of wave height at three distances from the sailing line and three vessel speeds are reported. Some vertical photographs of the vessel wave pattern are also presented.

Johnson, J. W. (1968a). "Ship waves at recreational beaches," Report HEL-12-7, Hydraulic Engineering Laboratory, University of California, Berkeley, CA.

This is a brief summary report discussing data collected by Hay (1967), Sorensen (1967), and Bidde (1968).

Johnson, J. W. (1968b). "Ship waves in shoaling waters." *Proceedings of the 11th Conference on Coastal Engineering*, London. American Society of Civil Engineers, 1488-98.

This paper replicates the material presented in Johnson (1968a). In addition, vertical photographs of vessel-generated wave shoaling on a 1:5 and 1:10 slope are provided. The photographs were taken in a small tank for depth Froude numbers ranging from 0.75 to 1.11.

Kurata, K., and Oda, K. (1984). "Ship waves in shallow water and their effects on moored small vessel." *Proceedings of 19th Conference on Coastal Engineering*, Houston, TX. American Society of Civil Engineers, 3257-73.

Model tests were run with a car ferry and a tug boat to measure the waves generated by these two vessels and to measure the effect of the waves on a moored small cargo ship. Tests were run at selected water depths for a range of vessel speeds that yield Froude numbers ranging from 0.3 to 1.5. Wave conditions were measured at five locations along a line normal to the sailing line. Data are presented for the period and height of the highest wave in a gauge record, plotted in non-dimensional form verses the depth and vessel length Froude numbers.

Maynord, S. T., and Oswalt, N. R. (1986). "Riprap stability and navigation tests for the divide-cut section Tennessee-Tombigbee Waterway - hydraulic model investigation," Technical Report HL-86-3, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

The focus of this model investigation was the stability of bank riprap when exposed to the wave and drawdown effects of a pair of selected barge-tow configurations. Some data are given for vessel-generated wave heights at a range of tow speeds.

Moffit, F. H. (1968). "Mapping of ship waves breaking on a beach," Report HEL-12-8, Hydraulic Engineering Laboratory, University of California, Berkeley, CA.

Stereophotogrammetry was employed to develop contour plots of the water surface for vessel-generated waves shoaling on sloped beaches. The vessels and beach slopes employed by Bidde (1968) were used.

Nece, R. E., McCaslin, M. R., and Christensen, D. R. (1985). "Ferry wake study," Final Report, Project Y-2811, Task 16, Washington State Transportation Center, University of Washington, Seattle, WA.

Prototype scale measurements were made of the waves generated by three classes of ferries operated by the Washington State Ferry System. Data on the test vessel hull geometries included the length, beam, draft, and gross net tonnage. Waves were measured at three points along a line perpendicular to the vessel sailing line. Vessel speed was determined from the vessel's engine speed and per formance characteristics. A total of 35 runs were made at speeds from 10 to 18 knots in deep water. Data reported for each run include the vessel speed and the maximum wave height from the wave record at each gauge location. The data show significant scatted owing the existence of waves from the wind and other vessels in the wave records.

Ofuya, A. O. (1970). "Shore erosion - ship & wind waves: St. Clair, Detroit & St. Lawrence Rivers," Report 21, Marine Engineering Division, Department of Public Works, Canada.

Vessel-generated wave measurements were made as part of a study of the relative effect of vessel and wind waves on the erosion of river banks. Repeated measurements were made for a 25-ft-long cruiser and individual measurements were made for single passages of 63 commercial vessels. The maximum wave height and the period of the highest and second highest waves were plotted versus vessel speed and distance from the sailing line for the cruiser. The wave energy given as the product of the maximum wave height squared and the related wave period were also plotted versus cruiser speed and distance from the sailing line. The data for the commercial vessel were grouped by water depth and distance from the sailing line. For each data group, the maximum wave height and the period of the highest and second highest waves were then plotted as a function of the vessel speed. Miscellaneous other plots are also presented. For all of the vessels studied, the vessel length, beam, draft, and displacement are given.

Permanent International Association of Navigation Congresses. (1987). "Guidelines for the design and construction of flexible revetments incorporating geotextiles for inland waterways," Working Group 4 of the Permanent Technical Committee, Brussels.

The authors give an equation that is similar to, but not identical to, the equation from Delft Hydraulics Laboratory (DHL) (given by Blaauw et al. (1985)) for predicting the height of the vessel-generated wave at the cusp location. As with the DHL equation, the height is given as a function of the vessel speed, the water depth, and the distance from the sailing line to the point of interest. No coefficient is required as the PIANC equation is only valid for tugs and motor vessels. For relatively low vessel speeds, the two equations yield similar results, but for higher speeds the PIANC equation yields significantly higher results than the DHL equation.

Saunders, H. E. (1957). *Hydrodynamics in Ship Design*, vol 2, Society of Naval Architects and Marine Engineers, New York.

The author gives an equation for the wave height at the bow of a vessel moving in deep water. It is given as a function of the vessel speed, the beam width, the entrance length of the vessel (distance from the bow stem to the point where the parallel middle body begins), and a coefficient the depends on the hull form. Values for the coefficient are plotted as a function of the ratio of the vessel speed to the square root of the vessel length.

Sorensen, R. M. (1966a). "Investigation of ship-generated waves," Report HEL-12-1, Hydraulic Engineering Laboratory, University of California, Berkeley, CA.

The waves generated by several prototype vessels operating in the Oakland Estuary are reported. The vessels included various tugboats, the City of Oakland fire boat, a Navy destroyer escort, a Coast Guard cutter, a small cabin cruiser, and a fishing boat. Reported data include the maximum height in a wave record and the associated period for a range of vessel speeds and distances from the sailing line. Froude numbers varied up to just under a value of 1.0.

Sorensen, R. M. (1966b). "Ship waves," Report HEL-12-2, Hydraulic Engineering Laboratory, University of California, Berkeley, CA.

Stereophotogrammetry was used to measure the wave surface contours for waves generated by a ship model having a generalized form. Ten vessel speeds, producing depth Froude numbers from 0.48 to 1.58 were investigated. Results are compared to predictions from various vessel wave theoretical analyses.

Also, results of field measurements of the waves generated by five different prototype vessels in the Oakland Estuary are presented and analyzed. (These tests are also reported in Sorensen 1966a.) Measurements of waves generated from five geometrically similar model vessels, 1.5 to 4.0 ft in length, are reported and analyzed. These tests were run at depth Froude numbers ranging from 0.4 to 0.9, and wave surface records were measured at four points along line normal to the model sailing line.

Sorensen, R. M. (1967). "Investigation of ship-generated waves," *Journal of the Waterways and Harbors Division*, American Society of Civil Engineers, Feb, 85-99.

This paper replicates the field data presented in Sorensen (1966a) with additional discussion of the experimental results.

Sorensen, R. M. (1969). "Waves generated by model ship hull," *Journal of the Waterways and Harbors Division*, American Society of Civil Engineers, Nov, 513-37.

This paper replicates the results of the stereophotogrammetric measurements of vessel-generated waves reported in Sorensen (1966b) with some additional discussion of the experimental results.

Sorensen, R. M. (1973). "Ship-generated waves," *Advances in Hydroscience*, Academic Press, New York, 9, 49-83.

This paper presents a summary of the characteristics of waves generated by a moving vessel and the field and laboratory studies of vessel-generated waves.

Sorensen, R. M., and Weggel, J. R. (1984). "Development of ship wave design information." *Proceedings of the 19th Conference on Coastal Engineering*, Houston, TX, 3-7 September 1984. Billy L. Edge, ed., American Society of Civil Engineers, New York, III, 3227-43.

The paper summarizes and evaluates the laboratory and field model data on vessel-generated waves that have been collected. Then, using the appropriate data from this summary, a ship wave height predictor model, in the form of a series of empirical equations, is developed. It gives the maximum wave height as a function of the vessel speed and displacement volume, water depth, and distance from the sailing line. This is an interim model that can be used for wave height prediction, but it can be improved upon given improved vessel geometry information. Also, a method is needed to predict the diverging wave period and direction of propagation out from the sailing line (see Weggel and Sorensen 1986).

Thompson, W. (Lord Kelvin). (1887). "On the waves produced by a single impulse in water of any depth, or in a dispersive medium." *Proceedings of the Royal Society of London*. Series A, 42, 80-85. "On Ship Waves." *Proceedings of Institute of Mechanical Engineers,* London. 409-33.

These papers give Kelvin's classic development of the pattern of waves generated by a point disturbance moving at a constant speed over deep water. The crest amplitudes along the diverging and transverse waves are also given, but owing to an asymptotic expansion that is invalid near the cusp locus lines, the theory yielded infinite amplitudes at the cusp points and no waves outside of the cusp locus line.

U.S. Army Corps of Engineers, Huntington District. (1980). "Gallipolis locks and dam replacement, Ohio River, phase I - advanced engineering and design study," General Design Memorandum, Huntington, WV.

An empirical equation for the vessel-generated cusp point wave height is given. This height is a function of the vessel speed and draft/length ratio as well as the channel section coefficient (see Balanin and Bykov 1965). As the distance from the vessel sailing line to the point of interest is not given, it appears that this equation is only valid in the vicinity of the vessel and probably for narrow channels. The equation is a simplification of an extremely complex set of equations, having some poorly defined terms that are given in a relatively obscure USSR publication.

Verhey, H. J., and Bogaerts, M. P. (1989). "Ship waves and the stability of armour layers protecting slopes." *Proceedings of the 9th International Harbor Congress*, Antwerp, Belgium.

The authors expand on the equation for maximum vessel-generated wave height given in the Permanent International Association of Navigation Congresses (1987) report. They introduce a coefficient similar to Gates and Herbich (1977) for considering the effect of vessel bow on the resulting wave height but only give a range of values for this coefficient depending on vessel hull type.

Weggel, J. R., and Sorensen, R. M. (1986). "Ship wave prediction for port and channel design." *Proceedings of the Ports '86 Conference*, Oakland, CA, 19-21 May 1986. Paul H. Sorensen, ed., American Society of Civil Engineers, New York, 797-814.

This paper expands the model for vessel wave prediction developed in Sorensen and Weggel (1984). Additional data are included, and the maximum wave height predictor equations are developed in terms of the vessel length, beam, and draft rather than just the displacement as done in the former model. A procedure, based on the theoretical limits at Froude numbers below 0.7 and equal to 1.0 and on experimental data in between, is developed for predicting the direction of propagation of diverging waves for a given vessel speed and water depth. Given the direction of propagation, the diverging wave period can then be calculated from linear wave theory.

Zabawa, C., and Ostrom, C. (1980). "The role of boat wakes in shore erosion (in Anne Arundel County, Maryland)," Final Report, Coastal Resources Division, Maryland Department of Natural Resources, Annapolis, MD.

A field study was conducted to compare the contributions of wind-generated and vessel-generated waves to bank erosion at selected representative sites. Vessel-generated waves were measured for selected vessels to be combined with boat passage counts for representative times during the boating season in order to obtain an indication of the level of vessel wave energy attacking the shore during a season.

Vessel wave measurements were made for two vessels, a 26-ft Uniflite Cruiser and a 16-ft Boston Whaler. A single wave gauge was employed and the vessels were run past the gauge at distances of 200, 150, 100, and 50 ft from the gauge. There were 25 runs of the first vessel and 35 runs of the second vessel. Besides reporting the usual maximum wave height in each wave record, the authors reported an average period and duration as well as energy density and total energy for each vessel wave record. The energy density and total energy in a wave record are determined from the record root mean square wave height. Vessel speeds yielded a range of depth Froude numbers from around 0.5 to 5. The test vessels were planing at many of the higher test speeds.

Appendix B
Notation

A	Coefficient in Equation 15
A', B'	Coefficients in Equation 25
A''	Coefficient in Equation 16
a, b, & c	Coefficients in Equation 23
B	Vessel beam width at its maximum point
C	Wave celerity
D	Vessel draft
E	Energy in a wave per unit crest width and wave length
d	Water depth below the still water level
d^*	Dimensionless water depth
F	Froude number
g	Acceleration of gravity
H_b	Wave height generated at a vessel's bow
H_m	Maximum wave height in a vessel wave record
H_m^*	Dimensionless maximum wave height
K	Coefficient in Equation 17
K_w	Coefficient in Equation 10 and given by Figure 5
L	Vessel-generated wave length

L_e	Hull entrance length (i.e., the distance along the sailing line from the bow stem to the point where the parallel middle body begins)
L_v	Vessel length
N	Cusp number measured out from the sailing line
n	Coefficient in Equation 19
S	Distance from vessel side to point of interest
S_c	Channel section coefficient (i.e., channel cross-section area divided by the wetted cross-section area of the vessel at midship)
T	Vessel-generated wave period
V	Vessel speed
W	Vessel displacement
w	Channel cross-section width at the water surface
x	Distance from vessel sailing line to point of interest measured perpendicular to the sailing line
x^*	Dimensionless distance from vessel sailing line to point of interest
α	Angle between sailing line and wave crest axis for leading wave when $F > 1$; coefficient in Equation 19
β	Coefficient in Equation 20
γ	Specific weight of water
δ	Exponential in Equation 20
θ	Angle between sailing line and wave propagation direction

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13. ABSTRACT (*Maximum 200 words*)

The waves generated by a moving vessel can disturb other vessels in navigation channels and marinas, damage shoreline structures, and cause the erosion of unprotected river banks. The erosion of unprotected riverbanks is of particular importance on the Upper Mississippi River System (UMRS).

In this connection, There is a need to be able to predict the characteristics of the free waves generated by a given class of vessel and mode of operation. These characteristics include the wave period and direction of propagation, but most importantly the wave height. The wave period and direction of propagation can be predicted analytically for a given speed and water depth of the vessel; however, the wave height depends on additional factors including the hull form and operating draft of the vessel, the distance from the sailing line, and possibly the cross-section geometry of the channel. Nine models, all having a strong empirical base for predicting the generated wave height, were identified and evaluated based on the vessels common to the UMRS. Most of the models are restricted in some way, such as being applicable only to to certain vessel types or to limited channel conditions. The three models having possible application to the UMRS were evaluated for their specific applicability and available field measurements of vessel wave height. This model evaluation produced limited results that can be significantly improved by comparison with additional field data.

The final section of this report includes an annotated bibliography on the available and pertinent literature on vessel- generated waves.

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