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.