CHAPTER 46

FERRY WAVE MEASUREMENTS IN DEEP WATER

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ABSTRACT

Data are presented for ship waves generated and measured in deep water. Results show the variation of maximum vessel waves with both vessel speed and distance from the vessel sailing line. Three automobile ferries of different configurations were tested. Field test procedures, limitations, and problems are described.

Introduction

Concerns have been expressed about possible increases in shoreline erosion which might be attributed to waves generated by specific classes of automobile ferries operating fairly close to shore on regular routes in the partially sheltered waters of Puget Sound, Washington, a deep-water estuary on the northern Pacific Coast of the U.S.A. A logical first step in investigating these concerns was to determine whether or not there were indeed significant differences among waves generated by ferries of various vessel classes.

The interest of coastal engineers in ship waves in the past has generally focused on problems associated with operation of ships in confined channels (e.g. Herbich and Schiller, 1984), on shore-mounted or pile-mounted wave gage measurements of waves generated by relatively smaller vessels (e.g., Sorensen, 1967) or on operation of vessels in water of finite depth (exemplified by early laboratory studies such as those reported by Johnson, 1958). The latter concerns arise when the depth Froude number $F_d = V_s / \sqrt{gd}$ (where V_s = vessel speed and d = water depth) becomes greater than about 0.6; the operating conditions for the Puget Sound tests yielded much smaller Froude numbers. Towing tank data were not available on waves generated by the ferries tested. Also, the combination of low Froude numbers and hull configurations placed the ferries out of the range of predictive formulae for wave heights (e.g., Weggel and Sorensen, 1986). Direct field measurements therefore were selected as the best approach. This paper describes the relatively low-cost, single-purpose tests and presents their results.

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Objectives

The specific objective was to determine maximum wave heights at various distances from the sailing line for each of three classes of ferries operating over their respective speed ranges in deep water. One representative ferry was tested for each vessel class. The three vessels tested were all double-ended ferries with diesel or diesel-electric propulsion. Characteristics of the vessels at their respective test conditions are listed in Table 1; English units are used.

Table 1
Characteristics of Ferries Tested

Vessel	Displacement[a]	Length[b]	Draft[c]	C_P[d]	C_B[e]
Sealth	2475	314	14.08	0.549	0.345
Yakima	2780	375	17.17	0.528	0.291
Klahowya	1650	301	13.5	0.618	0.310

Notes: a) Long tons, salt water
b) At water line, feet
c) Feet
d) C_P = Prismatic Coefficient = $\frac{\text{Displacement Volume}}{\text{Length x Midship Area}}$

e) C_B = Block Coefficient = $\frac{\text{Displacement Volume}}{\text{Length x Beam x Draft}}$

Test requirements dictated a straight course over which the vessel could be run at a constant speed so the wave pattern was established and non-varying relative to the ship, and so that repetive runs could be made past stationary wave gages. Necessary measurements were of wave height, distance of gage from sailing line, and vessel speed. A calm sea state with minimal tidal currents was desired. The degree to which these requirements were satisfied is discussed for each of the series of tests conducted.

Methodology

Waves were measured by three resistance-type spar buoy staff gages. The three-gage array was deployed in a direction essentially normal to the vessel sailing line along a single mooring line fixed to a permanent buoy at one end and kept in tension and position by being attached to a 9-m sailboat which served as a workboat operating under power at the other end (Figure 1). All electronics are located in the 3.6-m high 75-mm diameter staff portion of the buoys; the 150-mm diameter bottom section provides buoyancy, and the staffs receive their power from a generator on the workboat via a cable attached to the mooring line. The damper plate at the bottom of the spar buoy produces natural periods in heave and roll of 18 and 12 seconds, respectively, both much greater than periods of wind or ship waves at the test sites. Details of the gages have been provided previously (Nelson et al., 1983). The wave staffs were calibrated separately for each series of field experiments.

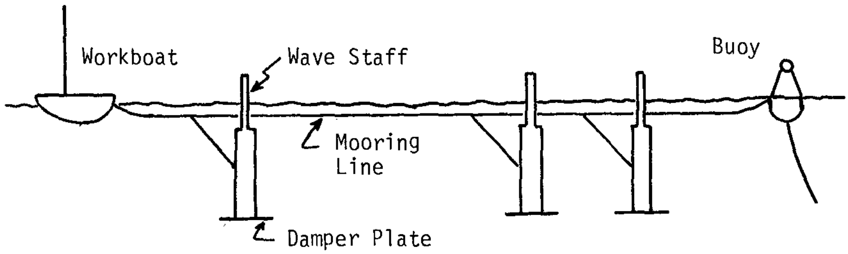

Figure 1. Schematic of wave staff deployment.

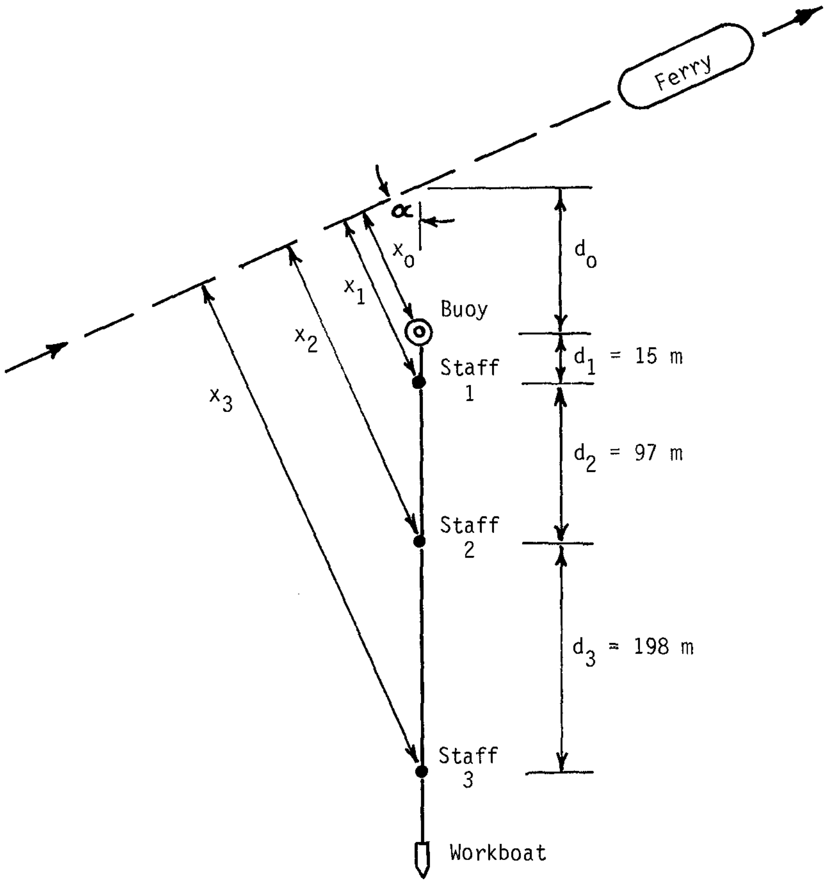

Figure 2. Schematic showing wave staff deployment in relation to ferry sailing line (not to scale).

Four analog recorder channels and one single-channel digital data requisition system were available; the latter could be switched from the output from one wave gage to another so that digital records of the highest ferry waves could be recorded as those diverging waves passed by each staff in turn.

Maximum wave heights were determined by two methods. The unfiltered value presented for each data set listed in Table 2 was obtained by direct visual inspection of the analog trace, using the maximum crest-to-trough reading within the wave train record. Vessel waves had frequencies between 0.25 and 0.5 Hz (2.5 to 4.0-second periods) with maximum wave heights ranging between 0.1 and 0.5 meters. Some coarse filtering was performed on the digital records, using the Fast Fourier Transform technique and a software package described earlier (Christensen, 1984). The filter selected rejected components with frequencies above 1 Hz and below 0.08 Hz. These frequencies are those of typical wind waves on the test dates and of the roll period of the wave staffs; the latter was selected to eliminate any effects of long period motions of the wave staffs caused by tension changes in the mooring line. The filtered data were plotted and the same visual procedure used to determine maximum wave heights. Where gaps occur in the 'filtered' results in Table 2, digital data were not available because of operator error or because the angle between the crests of the ferry-generated waves and the staff array was so small that the ferry waves passed through the array too quickly for more than one channel of digital data to be recorded.

The original project work plan called for both distances and vessel speeds to be obtained via aerial photography. The aerial work was restricted due to bad weather and/or the limitations on the altitudes at which aircraft were allowed to operate; the test sites were within the terminal control area of the Seattle-Tacoma International Airport.

The method used for determining distances for each data set is listed in Table 2. Those particular distances sought were x_1, x_2, and x_3, as identified on Figure 2. Distances d_1, d_2, and d_3 were 'unstretched' mooring line measurements. The six methods are described below:

(1) A photograph was used; the scale was determined by the known length of the ferry. The distance from the buoy to the workboat was measured. This was usually not equal to 310 m, because the mooring line would stretch under tension. Actual values of d_1, d_2, and d_3 were obtained by linear interpolation. The angle α was measured from the photo, also d_o. The "x" distances were determined by trigonometry, with the sailing line determined by extending a straight line back of the ferry. Due to aircraft elevation and/or lighting conditions, the individual wave staffs were not visible in the aerial photos.

(2) Same as (1), except that the distance x_o was estimated by an observer on the ferry because neither x_o nor d_o were obtainable from the photo.

Table 2-a; Summary of Results, Sealth

Dir.	Speed Kt	Dist. m	Staff No. 1 Unfilt. Height m	Staff No. 1 Filt. Height m	Dist. m	Staff No. 2 Unfilt. Height m	Staff No. 2 Filt. Height m	Dist. m	Staff No. 3 Unfilt. Height m	Staff No. 3 Filt. Height m	Method of Finding Dist.
E	10	225	0.23	0.19	335	0.16	0.13	565	0.47	0.42	(1)
W	10	55	0.15	0.16	165	0.15	0.17	390	-	-	(1)
E	10	90	0.23	-	210	0.20		425	0.17	-	(2)
W	10	90	0.19	0.17	200	0.19	0.18	425	-	-	(1)
E	15	100	0.28	0.26	215	0.21	0.20	440	0.19	0.17	(1)
W	15	90	0.24	0.21	200	0.16	0.17	425	0.22	0.17	(3)
E	17	90	0.30	0.32	200	0.29	0.27	425	0.26	0.23	(3)
W	17	90	0.37	0.35	200	0.32	0.28	425	0.32	0.31	(3)
E	18	90	0.46	0.43	200	0.27	0.27	425	0.25	0.26	(3)
W	18	110	0.40	-	210	0.30	-	435	0.30	-	(3)
E	18	110	0.30	0.32	210	0.28	0.26	435	0.27	0.25	(1)
W	18	75	0.38		175	0.34	-	365	0.35	-	(1)
E	17	90	0.25	0.23	175	0.21	0.21	360	0.27	0.26	(3)
W	15	90	0.30	0.30	175	0.20	0.17	350	0.22	0.19	(1)

Table 2-b; Summary of Results, Yakima

Dir.	Speed Kt	Dist. m	Staff No. 1 Unfilt. Height m	Staff No. 1 Filt. Height m	Dist. m	Staff No. 2 Unfilt. Height m	Staff No. 2 Filt. Height m	Dist. m	Staff No. 3 Unfilt. Height m	Staff No. 3 Filt. Height m	Method of Finding Dist.
S	16.3	120	0.22	0.22	230	0.12	0.16	440	0.08	-	(6)
N	16.3	120	0.15	-	230	0.15	-	440	0.13	-	(6)
S	16.3	115	0.19	0.23	225	0.15	-	435	0.13	0.16	(6)
N	14.2	115	0.23	0.22	220	-	-	420	0.10	0.13	(6)
S	14.2	115	0.21	0.20	215	0.27	0.27	410	0.13	0.14	(6)
N	14.2	110	0.25	0.21	210	0.21		400	0.13	-	(6)
S	10.9	110	0.19	0.20	210	0.22	0.21	400	0.09	0.14	(6)

Table 2-c; Summary of Results, KLAHOWYA

Dir.	Speed Kt	Dist. m	Staff No. 1 Unfilt. Height m	Staff No. 1 Filt. Height m	Dist. m	Staff No. 2 Unfilt. Height m	Staff No. 2 Filt. Height m	Dist. m	Staff No. 3 Unfilt. Height m	Staff No. 3 Filt. Height m	Method of Finding Dist.
N	13	110	0.30	0.28	210	0.21	0.27	400	0.08	0.15	(6)
S	13	110	0.21	0.23	210	0.25	0.26	400	0.25	0.20	(6)
N	10	110	0.19	0.22	210	0.11	0.19	400	0.11	0.11	(6)
S	10	150	0.17	0.14	245	0.13	0.14	435	-	-	(6)
N	10	115	0.23	0.20	195	0.13	-	345	0.13	-	(6)
S	10	105	0.30	0.27	140	0.22	0.23	215	0.14	0.13	(6)
N	13	105	0.26	0.25	140	0.16	-	215	0.16	-	(6)
S	<10	45	0.19	-	75	0.26	-	150	-	-	(4)
N	13	75	0.36	0.38	110	0.27	-	185	0.20		(6)
S	13	80	0.30	0.31	125	0.27	0.29	205	0.28	0.29	(4)
N	13	95	0.43	0.45	150	0.32	-	255	0.22	-	(6)
S	10	130	0.23	0.24	175	-	-	260	0.17	0.16	(4)
N	10	95	0.18	0.18	150	0.16	-	255	0.14	-	(6)
S	10	75	0.19	0.19	150	0.26	0.24	305	0.17	0.17	(5)

(3) No photographs were available. The distance x_o was assumed to be 76 m (250 ft), the 'target' value specified to the ferry pilot, α was assumed to be 90 degrees, and wave staff locations were assumed to be the same as determined from photos for adjoining runs.

(4) A photograph was used; the ferry again provided the scale. The same interpolation scheme was used to get distances between staffs. Because of the low 730 m (2400 ft) aircraft elevation, the larger photograph scale allowed measurements to be taken directly off the photo.

(5) A photograph was used, and the distance x_o measured directly. As not all of the staff array was included in the photograph, the other distances were assumed and were based on those determined in (4) above for an adjoining (in time) run.

(6) No photographs were available. The distance x_o and angle α were estimated by an observer on the ferry; wave staff positions were determined by assuming a ten percent stretch of mooring line and using trigonometry.

Although distances in Table 2 are listed to within 5 meters, actual accuracy was not that good. It is believed that the greatest source of error was in the distance x_o. The work boat was too small and too close to the ferry to allow use of the ferry's radar, and sextant readings from the workboat were not feasible. An estimate of the actual distance resolution is 15 meters; consequences are discussed later. All distances and wave heights were initially evaluated in foot units.

Aerial photographs were used to estimate the speed of the Klahowya, as speed pairs of photographs incorporating fixed points on land were obtained for the three engine speeds at which the ferry was operated. These speeds are not considered to be extremely accurate because the time intervals between successive photos and the resolution (± 1 second) of the camera clock visible in the photograph could produce errors as large as ten percent. Consequently, data obtained in previous special sea trials of the Sealth and Yakima were used to determine the speeds of these vessels. These prior data, in the form of propeller shaft rotation rate vs. vessel speed, had been taken very accurately through the use of shore-based radar. Their use was considered acceptable because the vessel drafts on the dates of the present tests were almost identical to those in effect during the sea trials. (At neither time was there a load of automobiles and/or passengers on board).

Field Tests - September 1984

The field tests were initially scheduled for the period 17-19 September, 1984. These dates followed immediately after cessation of the summer schedule for the ferry system so that three vessels could be withdrawn for one day each from regular routes in order to participate in the test program, and were scheduled to maximize daylight hours. Also, predicted tide ranges were small (1.5 m maximum) during daylight hours. The site selected was in deep water (depths in excess of 100 fathoms over most of the vessel path) in central Puget Sound about 15 km north of Seattle. The test ferry was to travel back and forth on the basically east-west path shown in Figure 3, past the wave staff array secured at the southerly end of the string to a permanent navigation buoy dividing the northbound and southbound traffic lanes. The wave staff array was aligned with the direction of current motion. Weather conditions were good and the light, southerly wind did not generate any significant wind waves so that the wave gage signals were uncluttered. There was considerable wave activity at the site which could be attributed to passing vessels. Since these waves has frequencies comparable to those which were to be measured it would be difficult to filter them out of the records obtained. Consequently, ferry runs were delayed until visible waves from larger vessels had cleared the area.

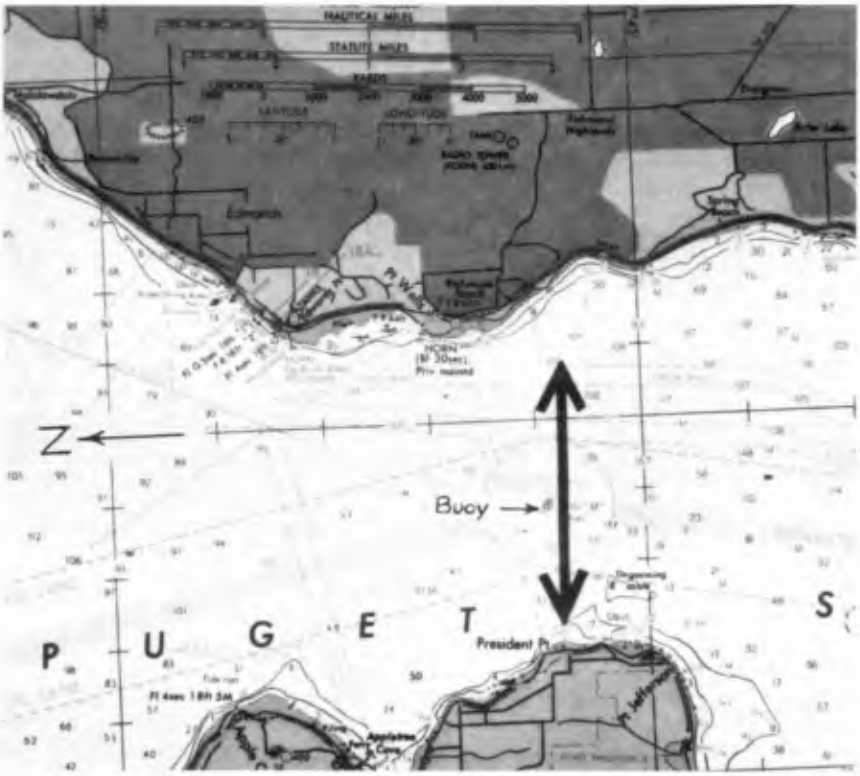

Figure 3. Central Puget Sound site, 17 September tests.

Tests were conducted, using the Sealth, on 17 September. Figure 4, which shows data obtained at the highest speed tested (18 knots) is representative of the results obtained. The values are listed in Table 2. The filtered and unfiltered data are combined on the single plot; it is noted that filtering did not yield any substantial reduction in the scatter. For the results shown in Figure 4, as with the measurements for the entire program listed in Table 2, errors in measurement of distance will account for only a small amount of the scatter. Even large distance discrepancies would not change the general pattern, especially at larger distances from the sailing line where variations in wave height with distance become smaller. Because ship waves are not entirely regular and repeatable, a number of data sets were obtained for the same ship speed.

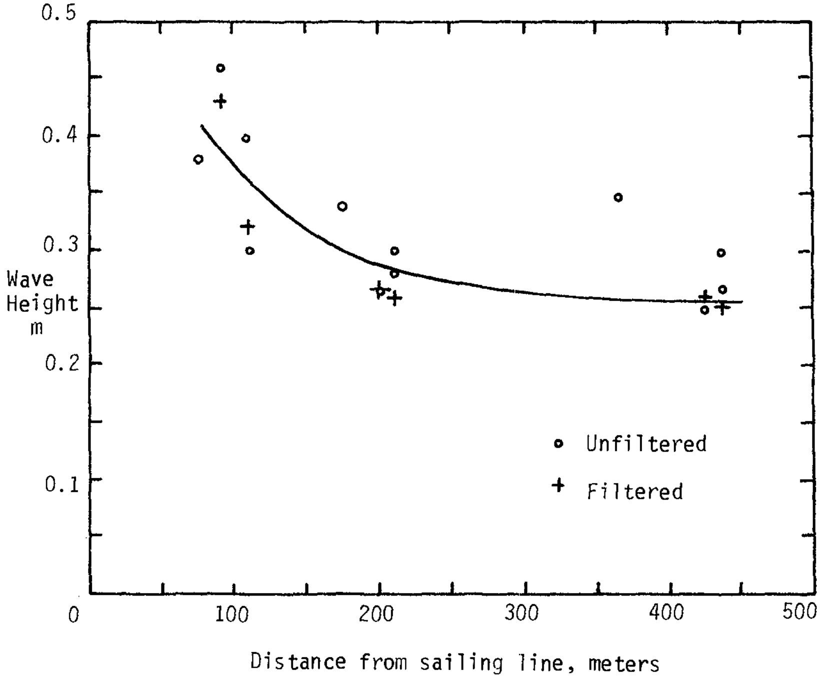

Figure 4. Maximum wave heights, ferry Sealth, 18 knots.

The wave through the plotted points on Figure 4 is strictly a hand-drawn visual fit, as the data were not considered sufficiently numerous to justify use of statistical techniques. The same treatment was applied to all data obtained for the three vessels tested; these curves and further details of the test program have been presented in the project report (Nece et al., 1985).

Mechanical problems experienced by other ferries required rescheduling of ferries, so there was no test vessel available on 18 September. Winds causing wind waves of height about the same as the ferry-generated waves, coupled with electrical problems in the staff array, caused the 19 September tests to be cancelled as well.

Field Tests - October 1984

Anticipated seasonal deterioriation of weather conditions along with uncertainty of availability of ferries for testing led to the selection of a different test location. The site chosen was on the west side of Blake Island, approximately 25 km south of the September site (Figure 5). A fundamental concern was protection from mostly prevalent southerly winds. A permanent mooring buoy provided attachment of the inshore end of the wave staff array which was strung out to the west from shore, so that the workboat was at the end of the string closest to the ferry path. The ferries' path was along a generally north-south line parallel to the west shore of Blake Island. The wave staffs were in depths of 10+ fathoms, and the ferries ran in depths generally of about 20 fathoms, so that deep water conditions prevailed.

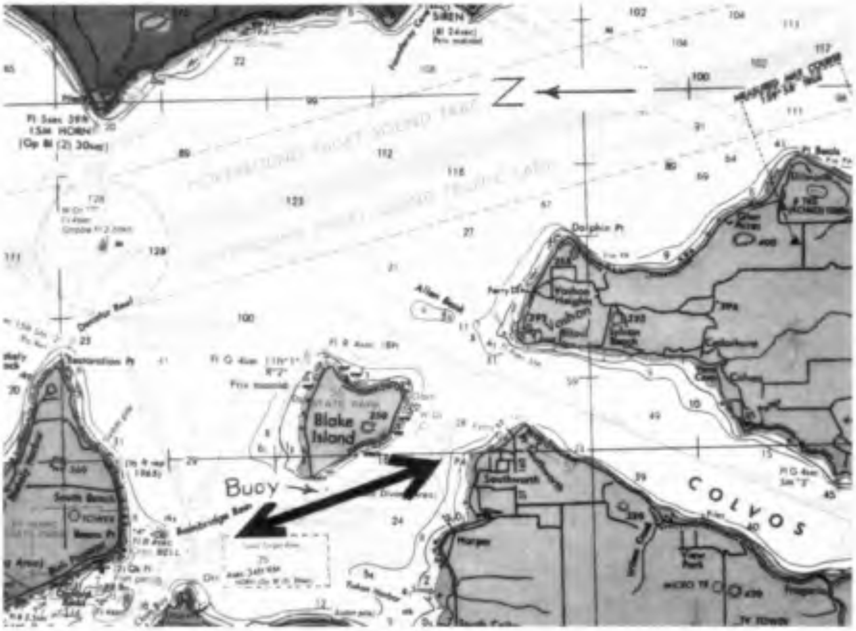

Figure 5. Blake Island site, 23 October tests.

Limited runs were made with the Yakima on the morning of 23 October. Low clouds and rain precluded aerial photography. Unanticipated strong north-flowing tidal currents at the site posed a problem. It was difficult to keep the wave staff array aligned normal to the ferry path. Near the end of the one-hour testing period it was decided to relax the requirement of trying to maintain the angle α at about 90 degrees; for the last runs, α was estimated at 60 degrees.

Maximum wave height vs. distance measurements are shown in Figure 6 for a vessel speed of 14.2 knots. The visual fit solid line curve through the data reveals apparently anomalous behavior, i.e., increase in wave height with distance from the sailing line. This same anomalous behavior was observed for the one run at a 10.9 knot speed.

Two possibilities were considered to explain this unexpected behavior. One was to consider the direction of ferry movement, and consequently that of its wave pattern as well. The currents could have caused some steepening of the vessel waves. In Figure 6 the dashed line applies to northbound ferry runs only.

Identification of maximum wave heights from the analog records was not clear-cut for the Yakima data. A complex demodulation analysis (see, e.g., Sobey and Liang, 1986, and Bloomfield, 1976) was applied to the 10.9 knot ferry speed data in an attempt to isolate the dominant frequency wave which is the ship wave. Results of this analysis indicated the presence of two dominant frequencies, 0.35 Hz and 0.45 hz. Based on the 10.9 knot vessel speed, the predicted frequency for waves at the boundary of the Kelvin ship-wave wedge was 0.35 Hz. Heights for the 0.35 Hz waves were determined and plotted (dashed curve) on Figure 7; the anomalous behavior indicated by results from the visual inspection of the filtered and unfiltered records (solid line) has been removed.

The complex demodulation analysis was applied to only the one set of data. The procedure holds the potential of isolating bow and stern waves, but was not pursued here because of the pragmatic objectives of the study.

Tests with the ferry Klahowya were conducted in the afternoon of 23 October. The wave staff array was allowed to drift more with the current, so angles α as estimated from the ferry or read from aerial photographs were considerably less than 90 degrees. Distances from the sailing line at which waves were measured then tended to be slightly smaller and more variable. Data for the 10 knot speed are plotted in Figure 8. Again, the curve shown is a visual best-fit line. The trend of decreasing wave height with increased distance from the sailing line is evident, although there is considerable scatter.

Because the currents present during the Klahowya tests were at least as strong as those during the Yakima runs, it is hypothesized that some of the apparently anomalous results obtained with the Yakima were associated with the behavior of the wave staffs when it was attempted to keep the array essentially normal to the direction of the current. Because of uncertainties associated with the Yakima data (all of which are listed in Table 2) they are not included in the summary curves presented in the next section.

Conclusions

Figures 9 and 10 are summary plots of wave height vs. vessel speed at distances of 100 and 300 meters, respectively, from the sailing line. Results are presented for the Sealth and Klahowya only; data for the Yakima are not presented because of the uncertainties discussed previously. The points shown on Figures 9 and 10 do not come from

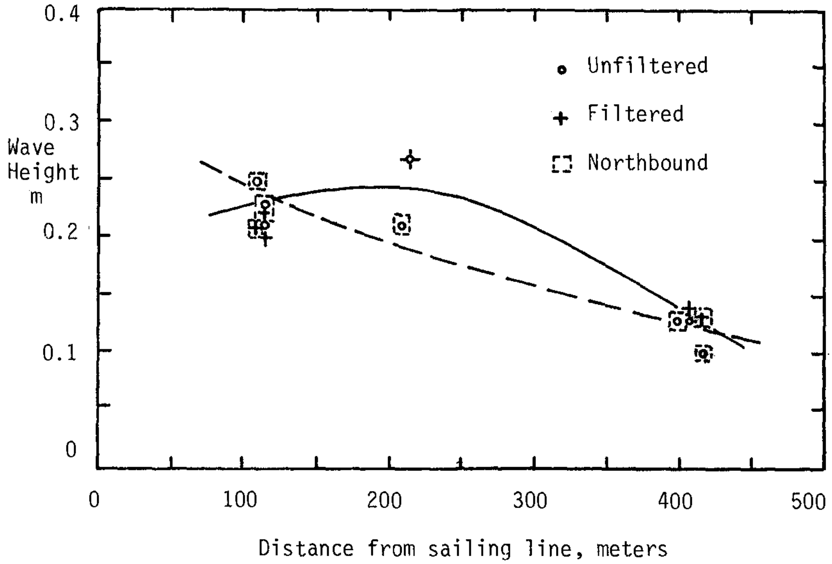

Figure 6. Maximum wave heights, ferry Yakima, 14.2 knots.

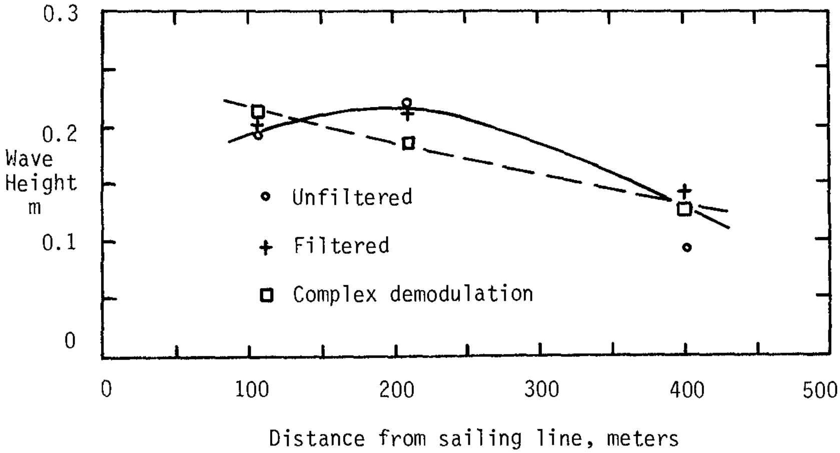

Figure 7. Maximum wave heights, ferry Yakima, 10.9 knots.

Table 2 but have been cross-plotted from the curves such as Figures 4 and 8 and others prepared for the remaining vessel speeds.

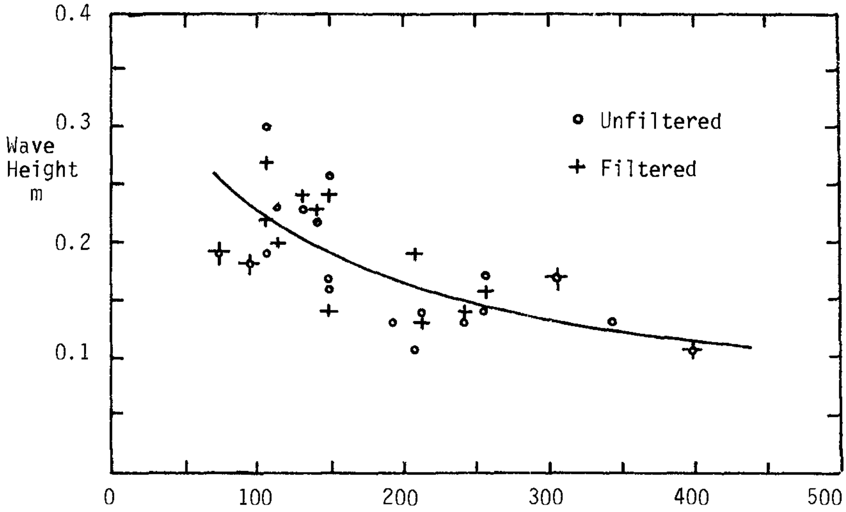

Figure 8. Maximum wave heights, ferry Klahowya, 10 knots.

Results clearly indicate that the different vessel classes do indeed produce waves of different height. Also, despite the uncertainties, it does seem apparent that the Yakima does generate the smallest waves as might be anticipated from comparison of hull geometries in Table 1. The results could also be used as a guide to vessel operation on specific routes in Puget Sound if wave generation is a concern.

Although the waves examined here are smaller than those usually of interest to coastal engineers, given the appropriate conditions the methodology could be applied to measurements of waves from larger vessels.

Acknowledgments

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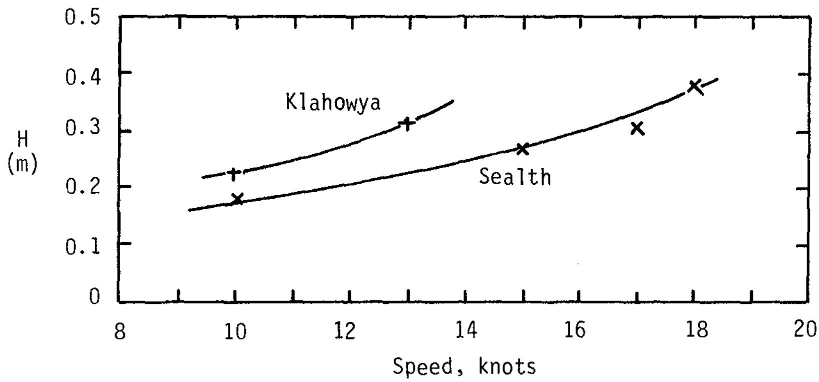

Figure 9. Wave heights at 100-meter distance from sailing line (from wave height vs. distance curves).

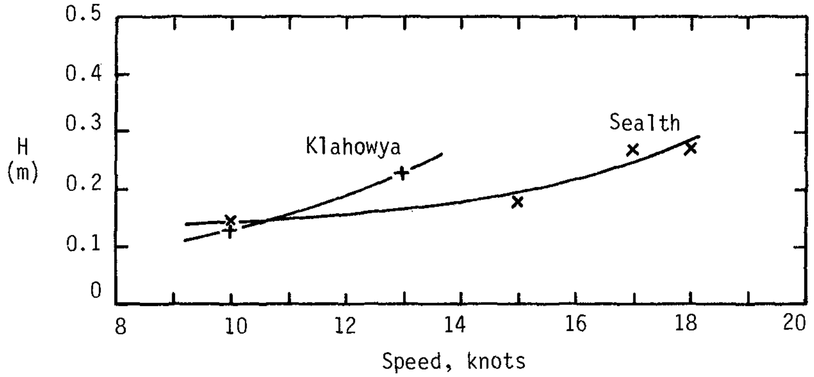

Figure 10. Wave heights at 300-meter distance from sailing line (from wave height vs. distance curves).

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