REPORT

WAVE ENERGY EVALUATION OF PASSENGER ONLY FAST FERRIES IN RICH PASSAGE

Rich Passage 1 Wake Wash Acceptance Test Results

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1.0 INTRODUCTION

The Rich Passage Passenger Only Fast Ferry Study is designed to investigate the feasibility of restoring Passenger Only Fast Ferry (POFF) service between Seattle and Bremerton (Figure 1-1). The study was initiated in June 2004 and is funded under federal grant programs administered by the Federal Transportation Administration (FTA) and Federal Highways Administration (FHWA) through Kitsap Transit. The grant programs are designed to support research and investigations of emerging transportation systems. Golder Associates Inc. (Golder) of Redmond, WA is providing study management and technical direction for physical and biological data collection, modeling, and analysis for the project.

The primary objective of the study is to develop the scientific basis to identify and minimize the potential impacts of candidate POFF vessels on the shorelines along the ferry route. This includes developing data and predictive tools that can be used to assess POFF operations prior to their implementation in terms of the potential for impact on Rich Passage shorelines, and which can be measured against a set of performance criterion. Implementing future POFF operations may require balancing tradeoffs between an exclusively vessel-based solution and a solution that also addresses shoreline effects.

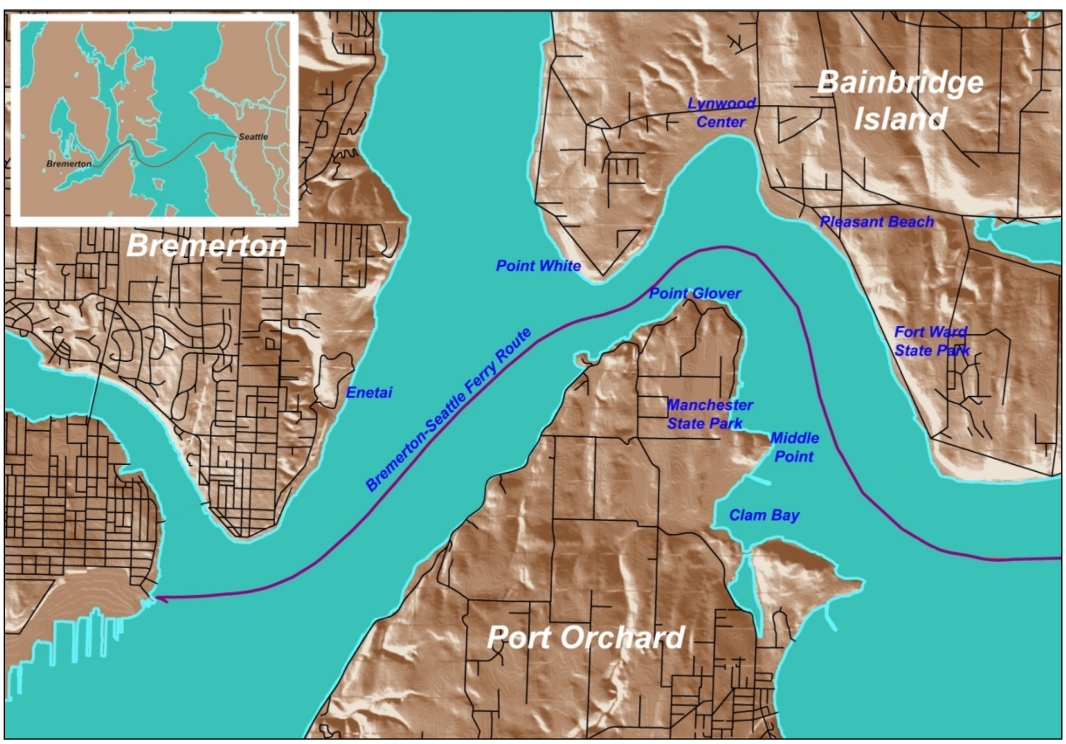

Figure 1-1: Seattle-Bremerton Ferry Route and Rich Passage Study Area

This report outlines the methodology and results of full-scale research tests with a new research vessel, the RICH PASSAGE I (RP1). This vessel was designed and constructed under guidance of the research program to validate models and to conduct in-situ beach response studies. The new RP1 is a high-speed, low-wake wash, foil-assisted catamaran (FAC) designed by Teknicraft Design Ltd, NZ (Teknicraft), and built by All American Marine, Bellingham, WA (AAM). The Teknicraft FAC design was optimized by means of computational fluid dynamics (CFD) modeling as described in Kandasamy et al. (2009). As a result of the research process on wake wash impacts in Rich Passage, new criterion were developed for vessel wake wash and performance (Osborne et al. 2009). The objective of the optimization process was to design a vessel that would meet the new wake wash criterion. The objective of the first phase of the full scale research tests is to validate the wake wash from RP1 against the wake wash performance criterion.

Section 2 of this report details the methodology used to measure the vessel dynamics and wake wash parameters of RP1. Section 3 describes the analysis and results of the wake wash acceptance testing. Section 4 provides a discussion of how the wake wash performance of RP1 compares to the wake wash criterion. Section 5 describes the additional wake wash testing and shore response studies conducted with RP1 in 2012.

2.0 METHODOLOGY

An iterative series of tests was conducted with RP1 at fixed foil, interceptor, loading, and speeds to confirm the vessel performance relative to the wake wash criterion and vessel specifications between October 27 and November 10, 2011. The testing plan is described in detail in the report *RP1 Testing Program* (Golder 2011), and described briefly in the sections below.

2.1 Testing Program

The wake wash acceptance testing of RP1 and in-water measurements of wake wash properties were conducted north of the Seattle-to-Bremerton ferry route in Port Orchard Reach just east of Illahee State Park (Figure 2-1). The test site was selected to have sufficient water depth for the vessel to operate in a super-critical hydrodynamic regime, and also to have comparable depths to those where RP1 will typically be operating such as Rich Passage. Water depths in the Port Orchard Reach area near Illahee are approximately 60 to 120 feet. This depth range would result in depth Froude numbers in the critical range at operational vessel speeds between approximately 26 and 38 knots.

RP1 was operated along the course to steer (CTS) for the testing program shown in Figure 2-1. Table 2-1 provides geographic coordinates and a description of the points labeled A through E on the CTS. Zones A-B and D-E are acceleration and deceleration zones where the pilot can make adjustments to vessel speed and heading before and after passing through the performance zone (between points B and D). The vessel maintains constant speed and heading in the performance zone. Two surface-riding wave buoys were deployed at points offset from and directly abeam of the CTS at point C. The distance between points B and D is long enough to provide adequate data for averaging vessel performance data for comparison with wake wash properties.

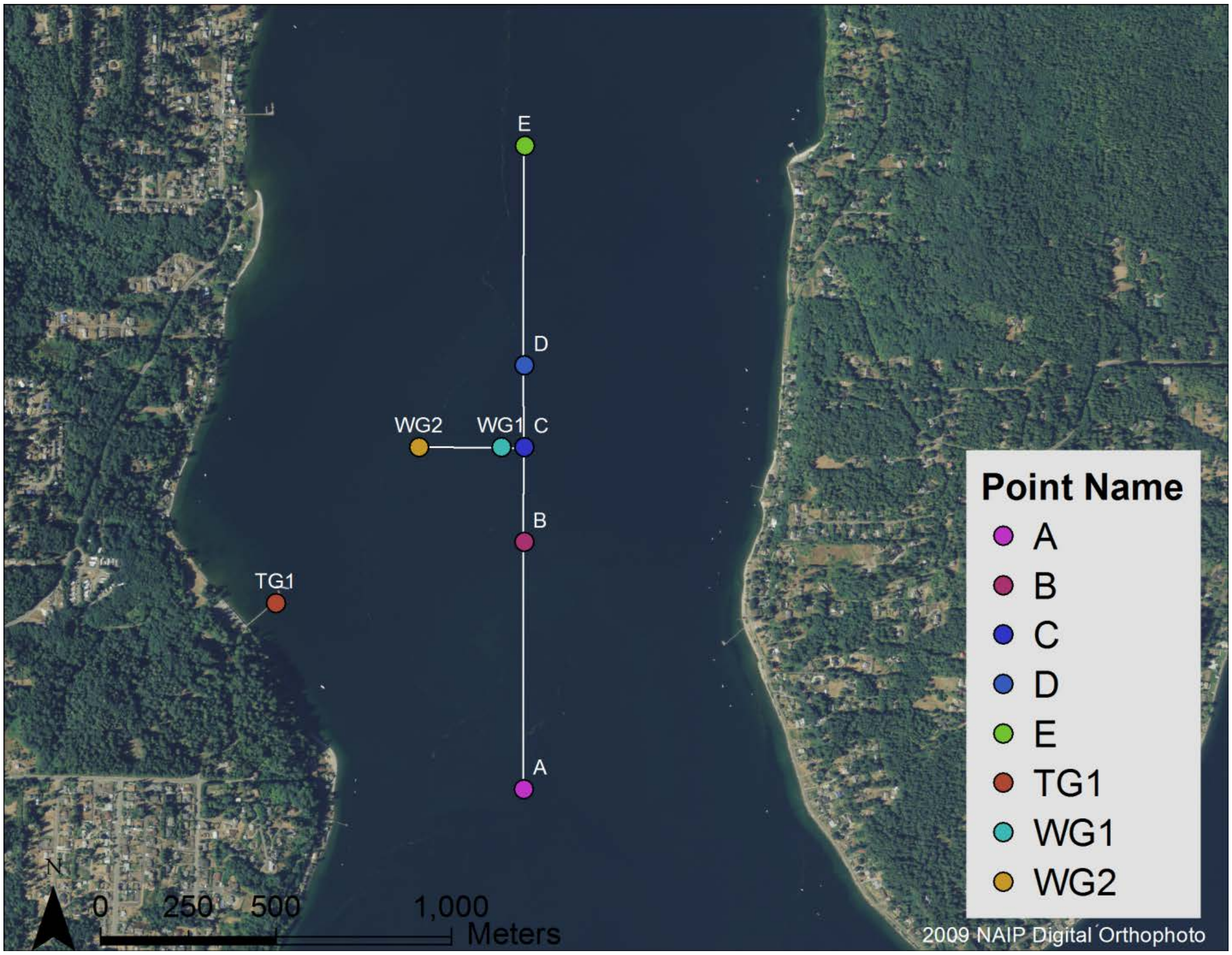

Figure 2-1: CTS and Location of Wave Gauges for Vessel Wake Wash Performance Trials for RP1 in Port Orchard Reach

Table 2-1: Coordinates of CTS and Wave Gauges for Vessel Wake Wash Performance Trials

Point Name	Latitude	Longitude
A	47°35'44.08"N	122°35'5.80"W
B	47°36'6.86"N	122°35'6.52"W
C	47°36'15.60"N	122°35'6.78"W
D	47°36'23.16"N	122°35'7.05"W
E	47°36'43.42"N	122°35'7.67"W
WG1 (60 m)	47°36'15.58"N	122°35'9.89"W
WG2 (300 m)	47°36'15.39"N	122°35'21.18"W
TG1	47°36'0.71"N	122°35'40.22"W

The test variants for the wake wash acceptance tests relative to the vessel specification and research criterion include the following:

- Engine speed (RPM) at 5 settings in the operating range between 1,950 and 2,200 RPM.
- Fully laden displacement (simulating 118 passengers, full fuel, and 3 crew).
- 3 foil angle settings and 2 interceptor settings.

The RPM, foil, and interceptor settings were determined from data collected during sea trials conducted by AAM and Teknicraft in Bellingham Bay between October 17 and 25, 2011. RP1 was run at a wide range of foil and interceptor settings during sea trials to determine the optimal settings for vessel performance including speed, trim, and fuel consumption. The data collected during sea trials was analyzed by Teknicraft to determine the settings to be used during wake wash acceptance testing.

At least six runs were conducted for each variant of test speed, loading, foil angle and interceptor setting (three in each direction on the CTS) to account for variability arising from vessel heading, and ambient winds and currents. More than 300 runs were conducted of which 180 will be used in the analysis below. Table 2-2 outlines the combination of runs for wake wash acceptance testing. Criteria for selection of runs for analysis are described in Section 3.2 below.

Previous wake wash trials have indicated a positive correlation between loading and wave energy (e.g. Osborne et al, 2007). Therefore, RP1 was ballasted with water bladders distributed throughout the passenger deck to simulate a fully laden condition during testing. In addition, the water storage tanks and fuel tanks were maintained at full capacity as much as practical.

Table 2-2: Vessel Wake Wash Acceptance Test Settings

RPM	Foil Angles (degree)			Interceptor Settings (%)	
1,950	0.6	1.0	1.2	20	27
2,050	0.2	0.6	1.0	16	25
2,100	0.2	0.6	1.0	16	21
2,150	0.2	0.6	1.0	17	20
2,200	0.2	0.6	1.0	15	18

2.2 Wave Gages

An array of two wave gauges was deployed at points offset from and directly abeam of the CTS at point C. The planned locations of the wave gauges (WG1, WG2) are shown in Figure 2-1 and planned coordinates are summarized in Table 2-1. A tide gauge (TG1) was deployed on a taut line mooring from the pier at Illahee State Park near the CTS to record average water levels during the trials.

The wave gauges (WG1, WG2) were TRIAXYS™ Mini directional buoys (hereafter referred to as wave buoy) deployed in a semi-free floating configuration (Figure 2-2) to allow un-restricted buoy motions in the wave field. A rubber tether approximately 30 feet in length was connected to the bottom of each buoy with a cannon ball weight on the end to keep the tether taught. In addition, a line was tied to the bottom of the tether that was run to a surface float. When necessary a small support vessel (Avon RIB or equivalent) would anchor near the buoy and tie off to the anchor line's float line to control the position of the buoy.

Figure 2-2: The TRIAXYS™ Mini directional Wave Buoy

2.3 On-board Measurements

RP1 is equipped with an on-board hull and foil monitoring system (HFMS) to log data on many aspects of the vessel's performance including pitch angle, roll angle, draft, and pressure distribution on the hull and foil, as well as fuel consumption and engine RPM, global positioning system (GPS) position, heading and speed. The wake wash produced by a high-speed vessel is influenced by a number of factors, including its loading, speed, hull shape, and depth of water. The hull shape is particularly important, and its influence is difficult to assess, since the draft and trim varies with speed and loading. Instruments comprising the HFMS are installed on RP1 to record the dynamic motion of the vessel (heave, pitch, roll), as well as its vertical and horizontal position in time. These data will be used to determine the trim of the vessel and lift created by the vessel's foil and the vessel's speed and position, for correlation with wake wash measurements. The HFMS will also provide quantitative measurements of the surface pressure distribution on the hull, including the areas around the waterjets and on the lower side of the foils (while vessel is at rest and under way). The surface pressure data will allow validation of the CFD models that have been applied to the optimization and design of the vessel and in particular quantification of the forces exerted on the hull through a range of operating speeds. Once the relationships between the vessel's operational variants and its wake wash performance are understood, an operation protocol can be established to optimize performance.

In addition to the data collected by the HFMS, several parameters were measured manually and recorded on the data entry sheets during testing including the following:

- Static draft (with no passengers on board) at three locations at start of day.
- Hourly fuel level readings.
- Number of persons on board and any other ballast.
- Ambient conditions along sailing line (presence and characteristics of surface waves, wind speed and direction, surface current speed and direction).

Accurate measurement of wake wash characteristics from RP1 requires calm sea surface conditions and minimal current. Prior to each test run the sea conditions were assessed by observers on the RP1 and also on a support vessel. In general, wake wash acceptance tests were suspended when any ambient surface waves or strong tidal currents were present.

3.0 DATA ANALYSIS AND RESULTS

The data collected with the wave buoys and on-board data collection system were analyzed to characterize the wake wash signature of RP1, to validate the vessel against the wake wash acceptance criterion and to provide data for verification of wake wash propagation models. The wake wash analysis involves computation of zero-up-crossing and zero-down-crossing wave heights, wave period, and wave energy density time series as well as spectral analysis to determine the distribution of energy as a function of wave frequency.

3.1 On-board Data

Data from the on-board HFMS were processed using MATLAB computational software, to calculate average, minimum, and maximum values during the time the vessel passed the buoys for each run. Preliminary plots were created in order to visualize and assess the quality of each trial run within the CTS performance zone. Figure 3-1 shows an example plot from a trial run on November 9, 2011. The plot shows (from top to bottom) vessel pitch and roll, foil and interceptor position, uncorrected vessel elevation (measure of vessel draft), speed as measured by two different on-board GPS units, and inboard/outboard engine RPM. The bulk statistics were combined with the processed wave buoy data to analyze the RP1 performance against the wake wash criterion. The vessel draft, hull and foil pressure, and foil strain data have been minimally processed and archived for use in CFD model validation if funding is available at a later date.

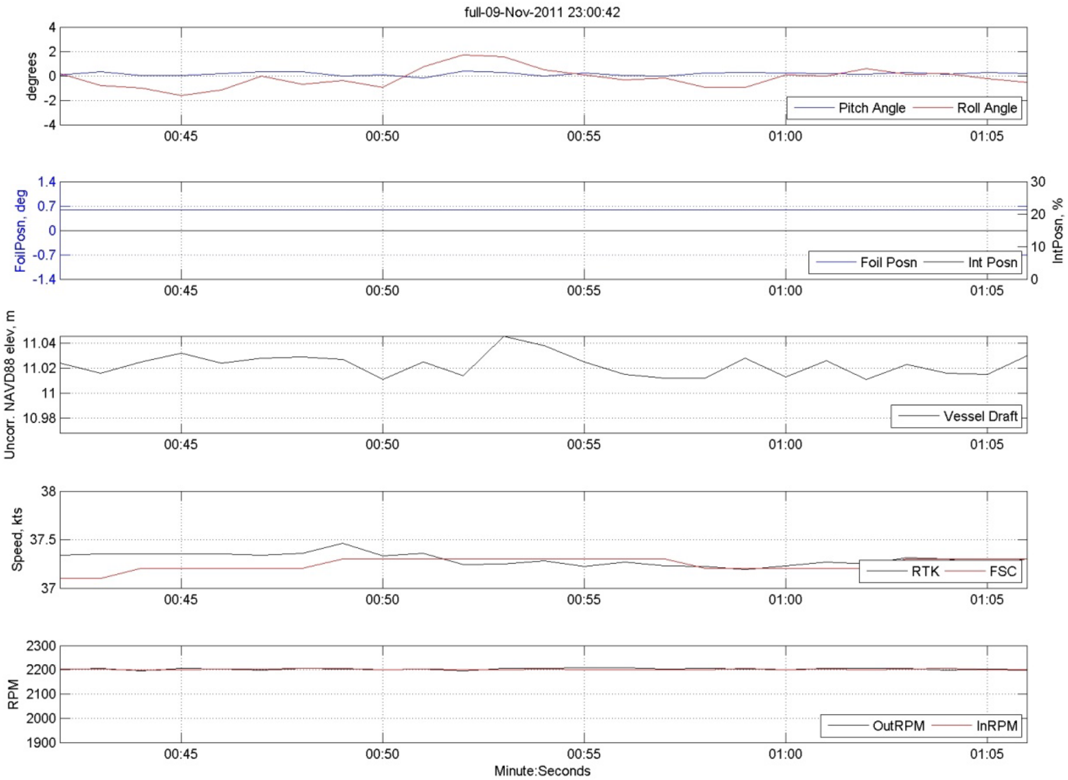

Figure 3-1: Preliminary plot of On-Board Vessel Data within the CTS Performance Zone during a Wake Wash Acceptance Test Run

3.2 Wake wash

Raw data from the wave buoys were processed using TRIAXYS post-processing software to provide measurements of horizontal displacement and heave (vertical displacement). Heave, as measured by the wave buoy, is representative of the water surface elevation (WSEL). A zero-crossing analysis of the WSEL time series was used to compute zero-up-crossing and zero-down-crossing wave heights, wave periods, and wave energy densities as a time series for each of the wake wash tests. A wave-by-wave spectral analysis was also performed to determine the distribution of energy as a function of wave frequency. Each time series was trimmed to include only the wave energy for a given test run. Further filtering of the 300 completed runs was done to discard data from further analysis for several reasons, including contamination from other vessel traffic, contamination from wind waves, and excessive turning of RP1 in the performance zone of the CTS.

The time series shown in Figure 3-2 is wake wash produced by RP1 at a speed of approximately 37 knots (2,200 RPM) and measured at the 300-meter buoy in Illahee Pass. The upper plot shows the free surface elevation and the wave height determined from the zero-crossing analysis, the middle plot shows the wave period determined from a zero-crossing analysis, and the lower plot shows the wave energy spectrum in the frequency domain. The wave period in the time series shows a smooth, steady decay characteristic of a high-speed vessel wake wash during the passage of the wave train, falling from a maximum of more than 5 seconds to approximately 1 second. The wave energy spectrum shows that energy occurs at a number of frequencies between 0.2 and 0.6 hertz (Hz) with a peak at approximately 0.3 Hz (3 seconds).

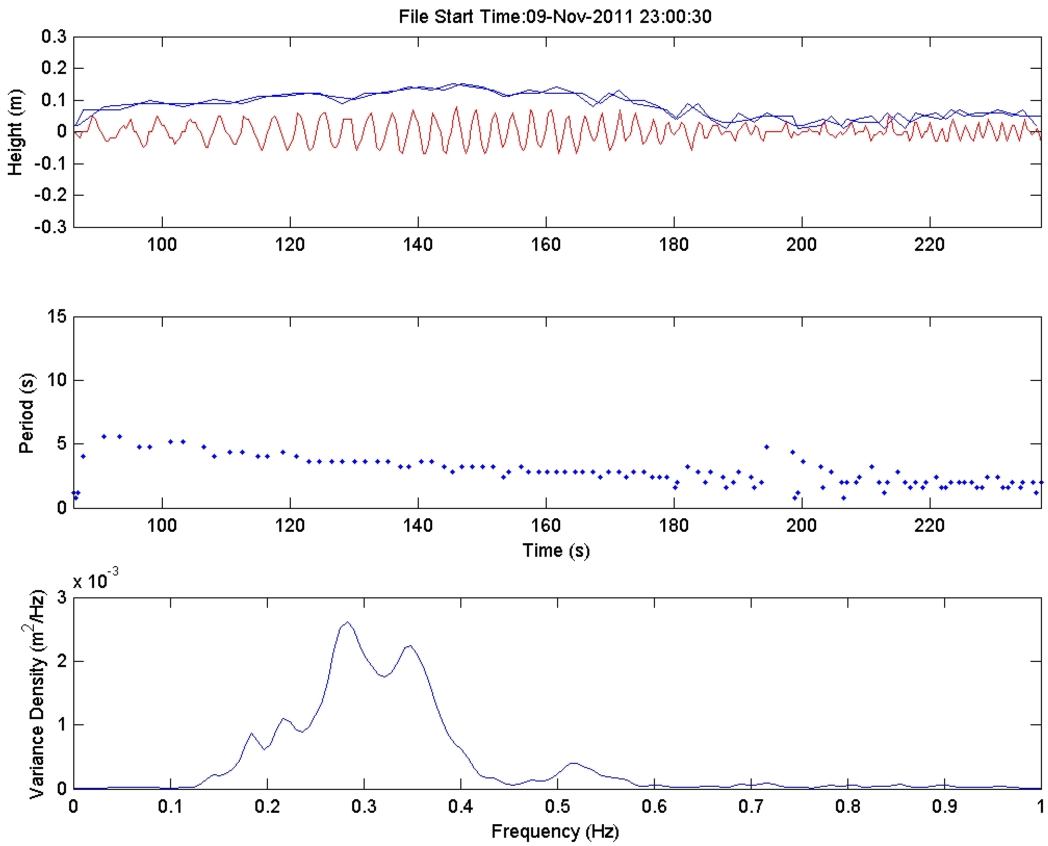

Figure 3-2: Time Series of Wake Wash Produced by RP1

3.3 Foil and Interceptor Settings

Wave height and period measurements for each combination of RPM, foil, and interceptor setting were combined to produce a single curve that accounts for variability arising from vessel heading, and ambient winds and currents. Figure 3-3 shows wave height and period measurements from four runs at 2,200 RPM (36-37 knots), with a foil setting of 0.6 degrees and 15% interceptor. A polynomial trend line was then fit to the aggregate data from the four runs to produce a representative wave height at the range of wave periods for these vessel settings. This process was repeated for each set of test variants.

In addition to the ambient wind and wave conditions, there was variability in the distance from the sailing line on the order of +/- 20 meters. The differences in distance from the sailing line may be partially responsible for some of the variability in wave height for a given wave period. This variability can be reduced through further data analysis.

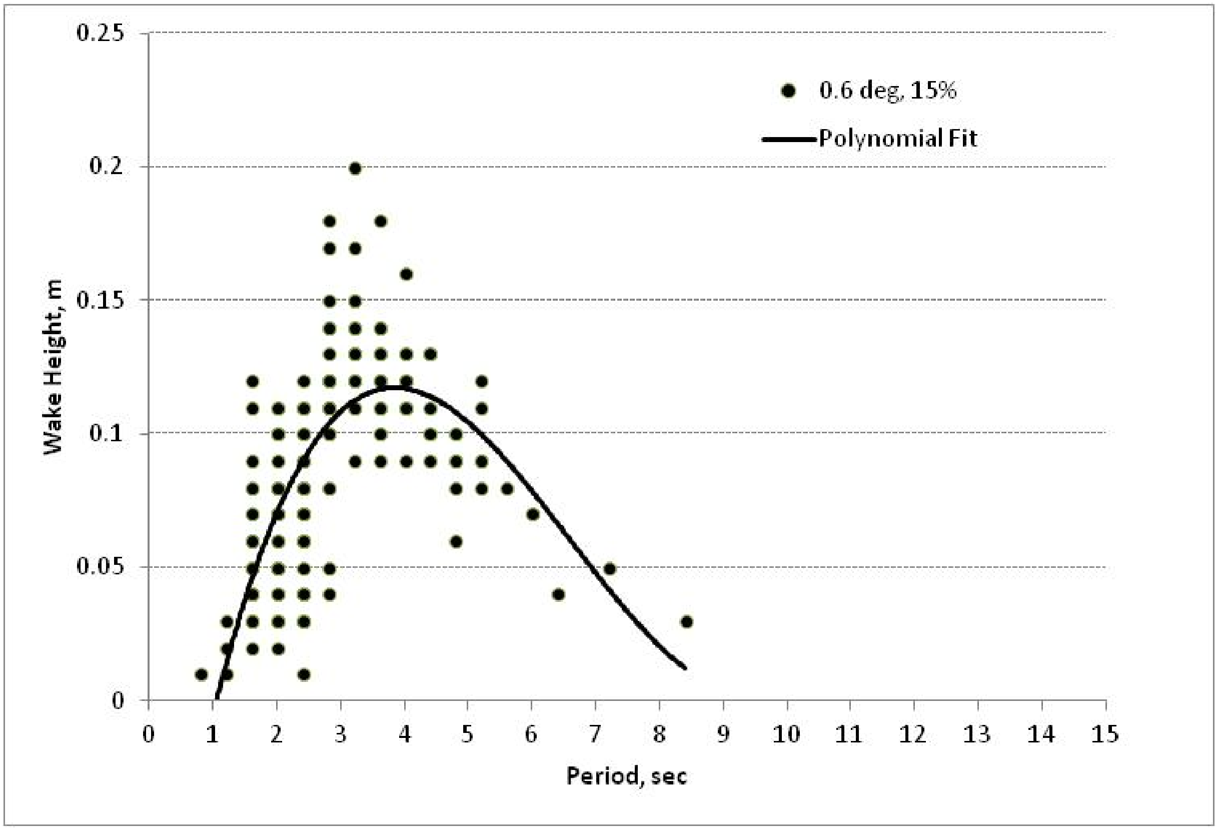

Figure 3-3: Variation in Wave Height with Wave Period at a Nominal Distance of 300 m for Settings of 2,200 RPM, 0.6 Deg Foil, and 15% Interceptor

A number of variables contribute to the vessel speed that RP1 can achieve for a given engine RPM while fully laden. These variables include vessel steering, tidal currents, and ambient wind and wind-waves (surface chop), as well as foil and interceptor settings. Figure 3-4 shows vessel speed with engine RPM for the full range of test settings in a fully laden condition. The scatter in vessel speed at each RPM is representative of different foil and interceptor settings. In general, a higher percentage of interceptor deployment decreases the speed RP1 can achieve for a given RPM setting.

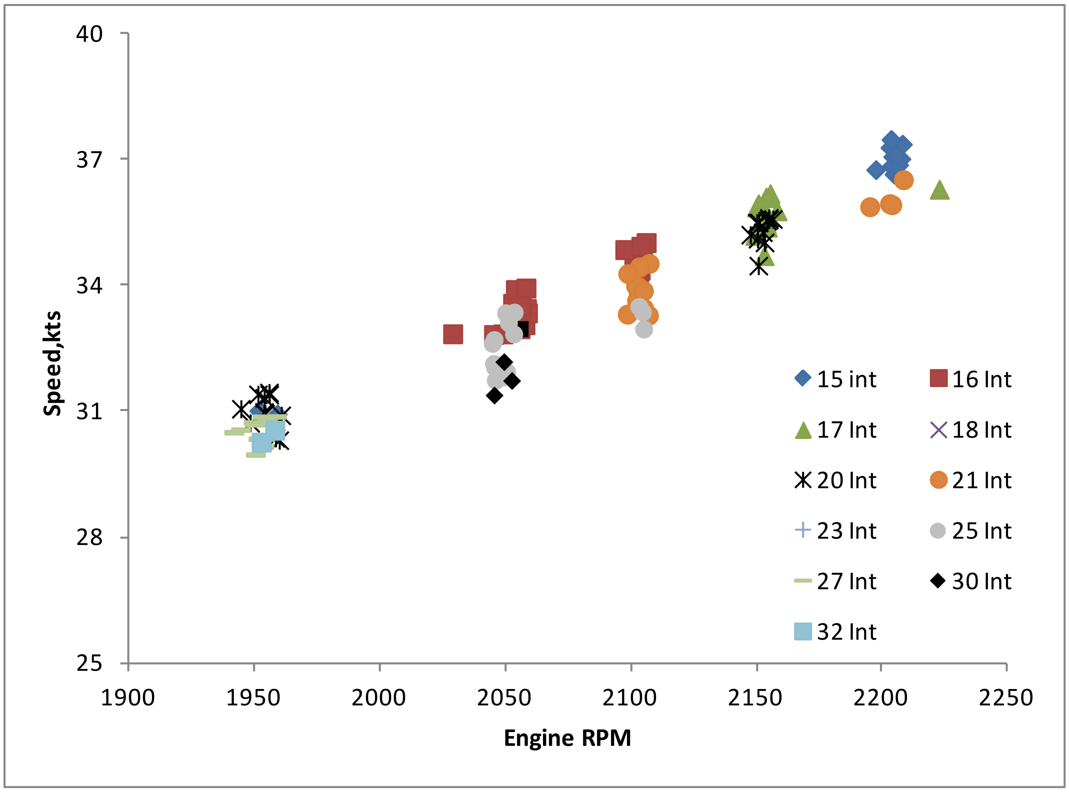

Figure 3-4: RP1 Vessel Speed with Engine RPM at Different Percentages of Interceptors

4.0 WAKE WASH CRITERION AND SPECIFICATION

The wake wash criterion for Rich Passage is specified at a range of wave periods from 1 to 15 seconds as follows and shown in Figure 4-1:

$$\begin{cases} T_j \le 3.5 : H_j \le 0.20 \\ T_j > 3.5 : H_j \le 1.16T^{-1.4} \end{cases}$$

Where T_j is the j^{th} wave period in a wake wash train in seconds, and H_j is the average wave height for waves at the corresponding j^{th} period of the wave in meters, as measured at a nominal 300 meters from the sailing line. The general specification document for RP1 includes a subset of the above wake wash performance criterion listed in Table 4-1, which the vessel must meet in order to be considered for in-situ beach response testing in Rich Passage.

Table 4-1. Wake Wash Performance Criterion in Design Specification for RP1

Vessel Condition	***Criterion***
Service speed (fully laden)	34-37 knot at 90% Maximum Continuous Revolution
Wake wash /wave height	<0.10 m @ 6 sec, 300 m dist. (deep water)
Wake wash /wave energy	< 630 J/m @ 6 sec, 300 m dist. (deep water)
Loading	Fully laden (118 passengers, 4 crew)

Figure 4-1 compares the wake wash criterion defined above to the average wave height with wave period of RP1, as measured at 300 meters from the sailing line for three settings. wake wash data from RP1 that is shown in the figure was collected while running the engines at 2,200 RPM (36-37 knots) using the lowest interceptor setting of 15% and foil angles of 0.2, 0.6 and 1.0 degrees. Although RP1 meets the specification at all three foil settings using 15% interceptor, a foil setting of 0.6 to 1.0 degrees show a better performance than 0.2 degrees.

The foil and interceptor settings shown in Figure 4-1 achieved the best performance for RP1. Figure 4-2 shows the best performance for RP1 compared to the Washington State Ferry (WSF) criterion, M/V Spirit, and M/V Chinook results. RP1 does not meet the full wake wash criterion (wave height at the full range of periods) when a larger percentage of interceptors are deployed. Other vessel performance attributes including speed and steering also decline and fuel consumption increases as the interceptors are more fully deployed.

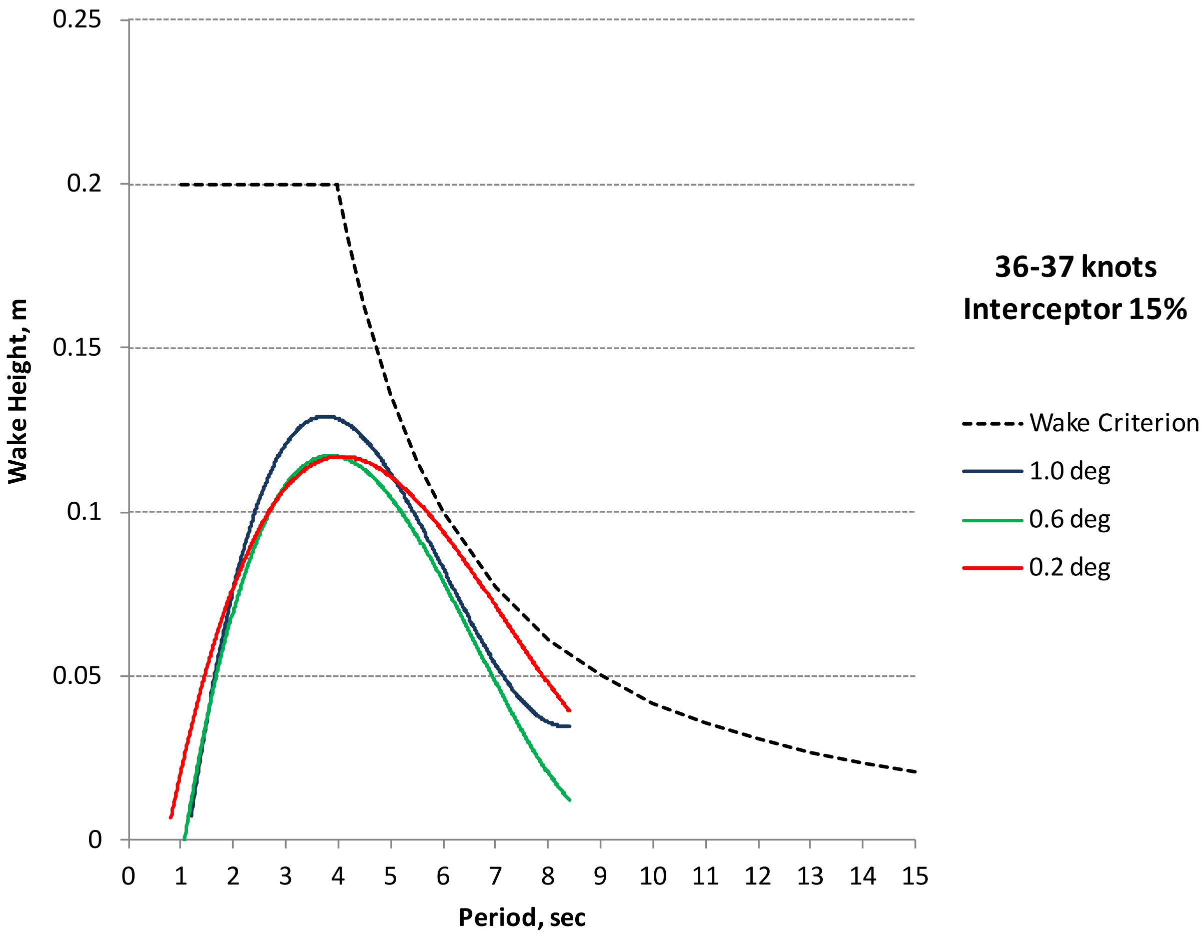

Figure 4-1: Average Wave Height with Wave Period from RP1 Measured at 300 m

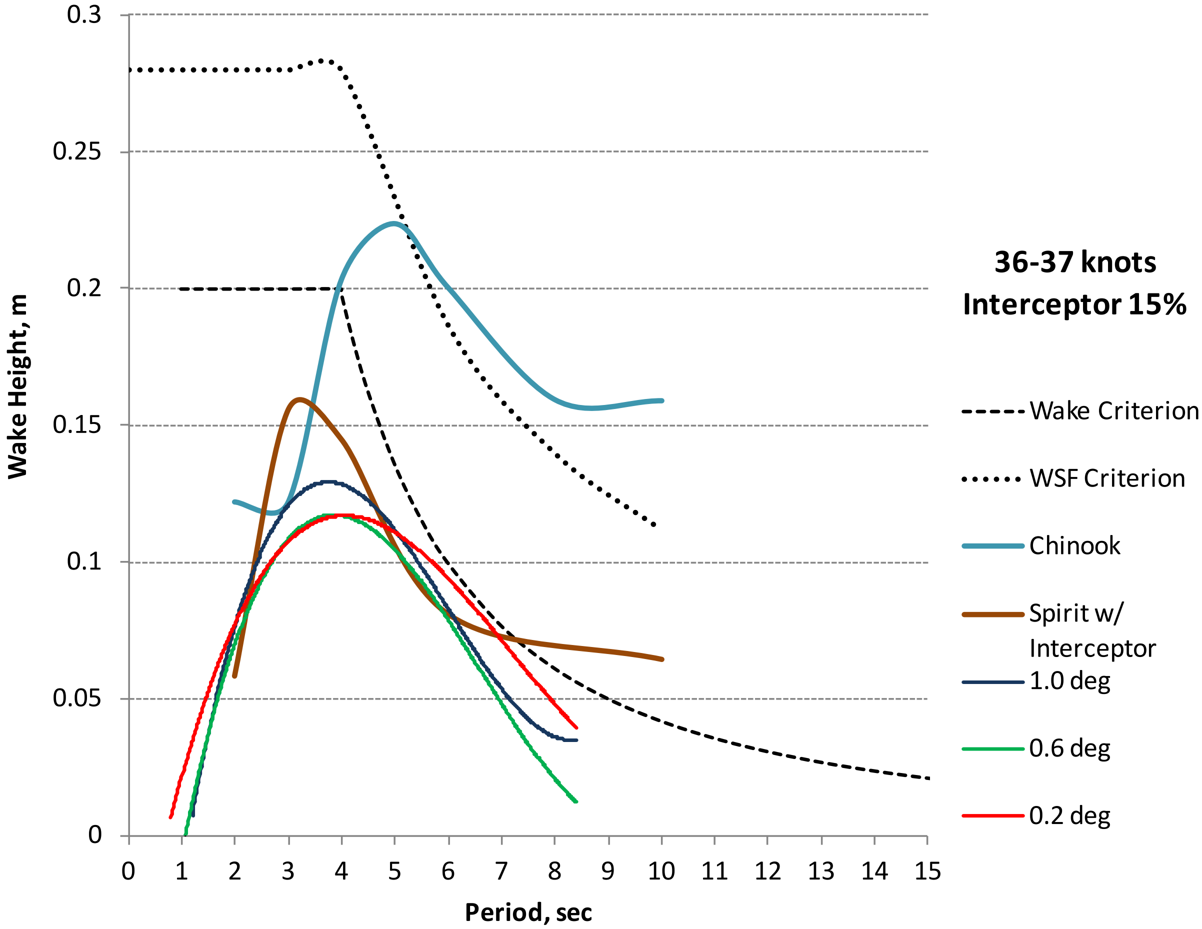

Figure 4-2: Average Wave Height with Wave Period from RP1 Measured At 300 m, Compared To The Washington State Ferry (WSF) Criterion

5.0 SUMMARY AND RECOMMENDATIONS

Rich Passage 1 meets the new wake wash criterion and wake wash specification running at a speed of 36 to 37 knots with a foil angle of 0.2 to 1.0 degrees and 15% interceptor at a distance of approximately 300 meters from the sailing line. RP1 should be tested with a smaller percentage of interceptor (< 15%) and foil angles between 0.6 and 1.0 degrees to optimize the vessel for wake wash performance. In addition, RP1 will be tested under different loading conditions to evaluate the performance at half load and light ship.

6.0 CLOSING

This is a final report on evaluation of RP1 against the wake wash criterion for fully laden conditions and general vessel specification document. This report supersedes previously issued drafts.

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7.0 REFERENCES

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