FULL-SCALE MEASUREMENTS AND IMPACT STUDIES WITH HIGH SPEED FOIL-ASSISTED CATAMARANS IN A WAKE SENSITIVE AREA

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ABSTRACT

Surface waves generated by high speed ferries operating at trans-critical and super-critical speeds can potentially cause adverse impacts to shorelines in confined waterways and environmentally sensitive areas. Repeated attempts to establish passenger fast ferry service on the Seattle-Bremerton route in Puget Sound have met with limited success due to such impacts. Trans-critical speeds along this route vary with tidal state in the range of 26 to 36 knots. Furthermore, the critical hump speed of most commercial-scale passenger only vessels is in the range of 15 to 26 knots. In general, speeds between the critical hump speed and trans-critical depth range should be avoided to reduce the potential for beach impacts in this area. The extent to which this condition might constrain the future of high speed operations on the route is the subject of this paper.

An experimental program was designed to test the application of a foil-assisted catamaran that exhibits high potential for commercial application in terms of both wakes and fuel efficiency. Results indicate a foil-assisted catamaran design optimized for low wake operations has potential to operate at trans-critical and super-critical speeds with significantly reduced impact compared with a conventional catamaran that formerly operated on the route.

1. INTRODUCTION

Fast passenger ferry operations that reduce travel time for commuters are often fundamental to the development and economic well-being of water-based communities. However, surface waves (wakes) generated by high speed ferries can potentially cause adverse impacts to shorelines and properties in confined waterways and environmentally sensitive areas (e.g. Nanson et al., 1994; Parnell and Kofoed-Hansen, 2001; Bauer et al., 2002). In Puget Sound for example, repeated attempts to establish passenger fast ferry service over the past two decades on the Seattle-Bremerton route that passes through Rich Passage have met with limited success as a result of such impacts (PI Engineering, 2005).

Limited full-scale data are available from high speed passenger ferries to evaluate vessel performance, assess wake impacts of candidate operations, and provide guidance on possible design improvements. The Rich Passage Passenger Only Fast Ferry Study (PI Engineering, 2005) was designed to investigate the feasibility of restoring a passenger only fast ferry (POFF) service between Seattle and Bremerton with particular focus on Rich Passage, the narrowest section of the waterway constrained by landmass points to the north and south. The objective of the study is to establish criteria necessary to minimize wake damage from potential POFF operations with crossing times of less than 35 minutes. The approach has been to develop scientific and technical baseline data, and to assemble an integrated system of predictive tools to identify and evaluate the impacts of potential high speed vessel operations on the shorelines along the ferry route.

This paper examines the constraints on operation of high speed POFF on wake sensitive shorelines through Rich Passage taking into consideration the distinctive characteristics of wakes from high speed vessels that impact beaches along the ferry route. Evidence in support of a new operational wake criterion for the wake sensitive area is drawn from in-situ impact studies and past experience with POFF and from full-scale field trials and CFD optimization studies with candidate vessels that include a foil-assisted catamaran.

2. OPERATING CONSTRAINTS FOR WAKE SENSITIVE AREAS

A vessel wake observed at the shoreline in a coastal, estuarine, or fluvial environment occurs as a sequence or group of waves. The characteristics of the wave group observed at the shoreline depend on a large number of variables related to the moving vessel including position, heading, and distance from shore, speed, hull geometry, trim and displacement, as well as the properties of the ambient water body including depth contours, presence of currents, or wind waves.

2.1 Variation in Maximum Wake Height with Vessel Speed

For any given vessel and constant water depth, an increase in speed will lead to an increase in the height of the maximum wave in a wake train (H_{max}) up to a certain speed. Beyond that speed, the maximum wave height will decrease. The speed at which H_{max} occurs is often referred to as the *hump* speed. The hump occurs when the ship produces a wake with a wavelength that is one-half the length of the ship.

The vessel speed at the hump (V_{hump}) can be derived from the dispersion relation (the relationship between wave speed and wave length) for linear waves substituting the length of the ship (L) for wavelength and the local water depth (h):

$$V_{hump} = \sqrt{\frac{gL}{\pi} \tanh \frac{\pi h}{L}} \qquad (1)$$

Note that V_{hump} occurs at a *vessel length Froude number* (F_L) of 0.56 where F_L is defined as:

$$F_L = \frac{V}{\sqrt{gL}} \qquad (2)$$

According to eq. 1, V_{hump} becomes constant as the water depth h becomes large for a vessel given L. Also, shorter vessels get over the hump and begin to show a reduced wake at lower speeds than longer vessels.

For the case of the Seattle to Bremerton ferry route, water depths vary between 20 and 30 m, and typical passenger only vessels have lengths that vary over a similar range. Therefore hump speeds are typically in the range of 15 to 25 knots for most conventional commercial catamaran craft in this area. In general, it is important to avoid operations around the hump speed in cases where wake minimization is an objective, because the vessel will, in general, produce it largest wakes around these speeds. Fuel consumption is also very high at the hump speed.

2.2 Super-critical and sub-critical wakes

The term *super-critical* is sometimes used to describe high-speed vessels while the term *sub-critical* is used to describe displacement vessels traveling at slow speed. Super-critical refers to the state where the vessel is moving faster than the speed at which a wave of the same length can travel in that depth of water. The wake produced by a super-critical vessel is different from that produced by a vessel moving at sub-critical speed. The super-critical condition occurs when the speed of the vessel exceeds that of a long wave in the same depth of water. It can be determined using the *depth Froude Number (F_h)*:

$$F_h = \frac{V}{\sqrt{gh}} \qquad (3)$$

Fig. 1a illustrates an example wake pattern generated by a vessel moving at 38 knots in water that is infinitely deep. Since h is infinite, F_h = 0 and the condition is sub-critical. The wake is composed of two parts: diverging wakes that move away from the vessel at an angle of up to 35.27^o and transverse wakes that move in the vessel's direction. Both types of wakes theoretically exist only within a cone set at 19.47^o from the vessel.

The wavelength and speed of the wake can be found from linear wave theory. As the vessel speed increases, so does the speed, or *celerity*, of the wake. A point will be reached where the vessel is moving faster than the celerity of the transverse wake and the transverse wake is shed. Beyond this critical point (i.e., if the vessel maintains a speed equal to or greater than this speed and the depth remains the same or decreases) the wake will assume a super-critical wake pattern, which is composed only of diverging wakes. Fig. 1b shows the wake pattern for the same case as shown in Fig. 1a, but in a depth of 30 m. In this water depth, F_h = 1.14 and the resulting wake pattern is super-critical. The pattern is broader and there is no transverse component following the vessel. The spacing between wave crests in Fig. 1a varies considerably for the diverging wakes, but only slightly for the transverse wakes. The variable spacing corresponds with a variation in the time it takes for successive wave crests to pass a fixed point, in other words wave period (T). Corresponding wave periods are superimposed on the wake pattern as color contours in Fig. 1. It can be seen that the transverse wave period is approximately 12 seconds, while the divergent wave periods vary between about 1 second close to the sailing line and 10 seconds away from the sailing line. The speed range around F_h = 1 is known as the *trans-critical* speed range; it will be discussed below.

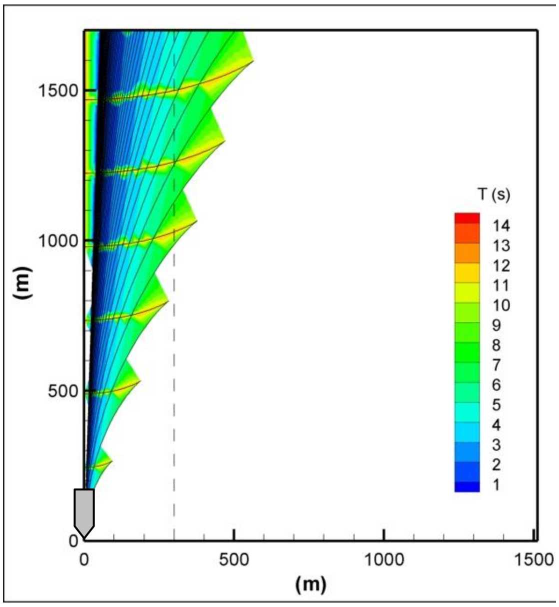

Fig. 1a. Wake period for 38 knot vessel in infinite depth water

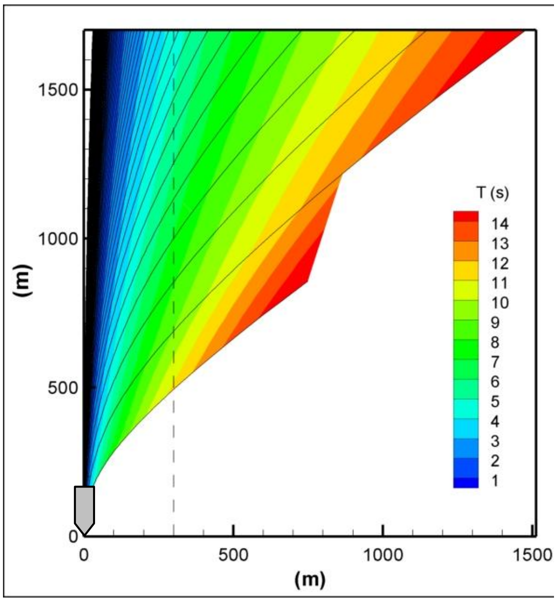

Fig. 1b. Wake period for 38 knot vessel in finite depth water

The spatial wake patterns described are clearly visible to the naked eye; however, most measurements of wakes are obtained from fixed, single-point instruments. Wave data from these instruments is in the form of time series of water surface elevation. Computer software is used to convert this data into height and period form.

Fig. 2 shows the time series of wake periods of the two cases shown in Fig. 1 measured at a wave gauge 300 m off the sailing line. The super-critical wake pattern (finite depth) arrives earlier than the infinite depth case, although the temporal decay in period of the diverging wake will be similar for the two cases. The period of the sub-critical wake will not oscillate between that of the diverging and transverse parts as appears in this theoretical example, but will be dominated by the component with the most energy. The differences between super-critical and sub-critical vessel wakes have been illustrated previously with time series measurements (Osborne et al., 2007). In summary, if the vessel is in a sub-critical regime (i.e. $F_h < 1$) and dominated by the transverse waves, then the wake appears to be monochromatic (i.e., all the energy is at a single frequency or period); if the boat is super-critical, then the wake will contain energy over a range of frequencies with the longest period waves arriving at the measurement point first and the shortest waves last.

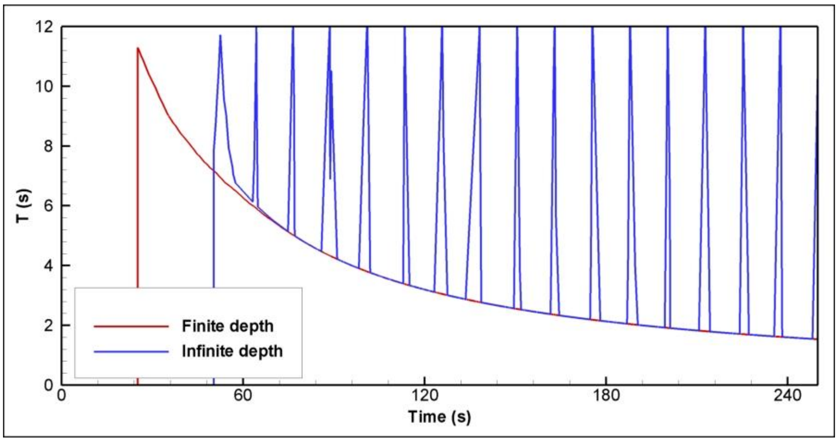

Fig. 2. Comparison of wake period at 300 m from the sailing line for finite and infinite depth cases

2.3 Trans-critical wakes

A sub-critical wake pattern contains both diverging and transverse wakes. Below the hump speed, the two wake patterns are not impacted by the depth. Beyond the hump speed, the transverse wakes begin to "feel" the bottom and become less *dispersive* (i.e., less able to transfer energy from one wave to another). At the critical speed, F_h=1, the vessel and the wake are both moving at the local long wave speed, $\sqrt{gh}$. In reality, this behavior is not instantaneous but occurs over the *trans-critical* range. The breadth of this range around F_h=1 is unclear, but estimates vary as broad as 0.84 to 1.15 (Husig et al., 2000) and 0.85 to 1.1 (PIANC, 2003).

At the critical speed, a single transverse wave will develop parallel to the vessel stern. Since energy is constantly pushed into this wave and the wave cannot disperse, the transverse wave can grow in size very quickly (MCA, 2001). If a vessel operates at the critical speed for too long the wake will extend further and further out from the sailing line and build in height. The pattern will change depending on the duration of operation at this speed. There will also be a dramatic increase in wave making resistance of the vessel (PIANC, 2003) and, consequently, fuel consumption. From both a wake minimization and economic standpoint, it is important that a vessel not be operated at the critical speed for long periods of time. Another effect of these very long trans-critical waves is shoaling in shallow water resulting in an increase in wave height and higher wave energy per unit area of the wave. Fig. 3 shows a photograph of a foil-assisted catamaran (M/V Spirit) slowing down and passing through the trans-critical range; a large, quickly developing wave alongside the ship is clearly visible. For a high speed vessel, the optimum operational range is often the super-critical range, if depths permit. Fig. 4 shows a photograph of the FAC M/V Spirit operating in the super-critical range.

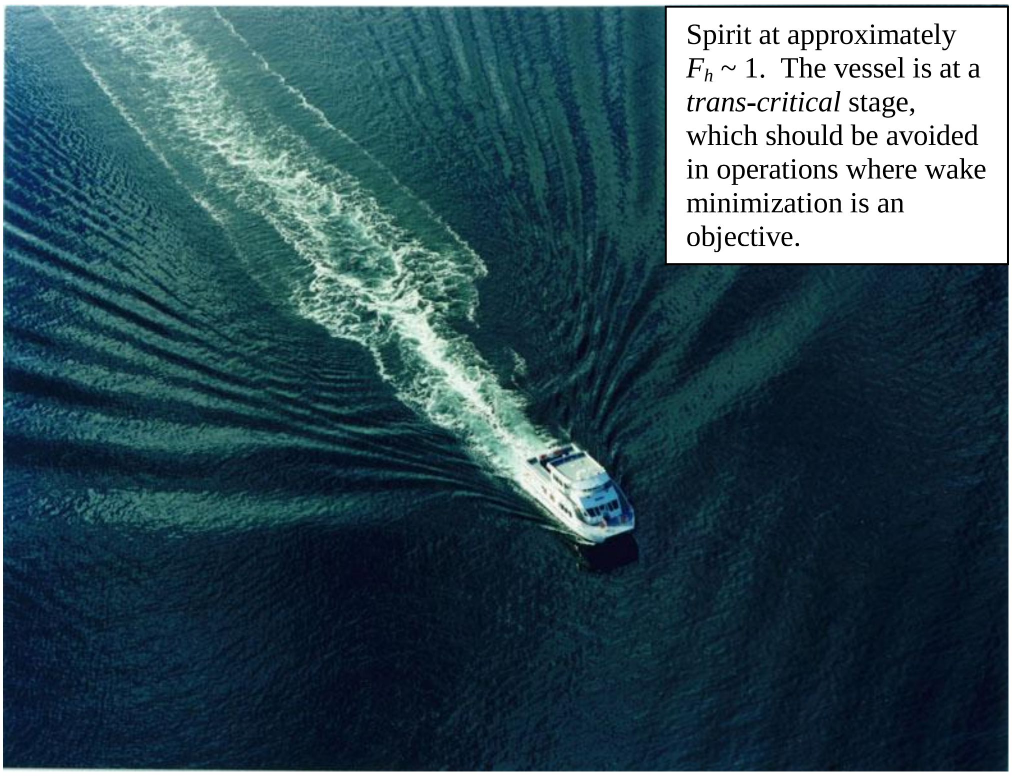

Fig. 3. Photograph of Spirit slowing down and passing through the trans-critical speed. Note the large, long waves building alongside the vessel.

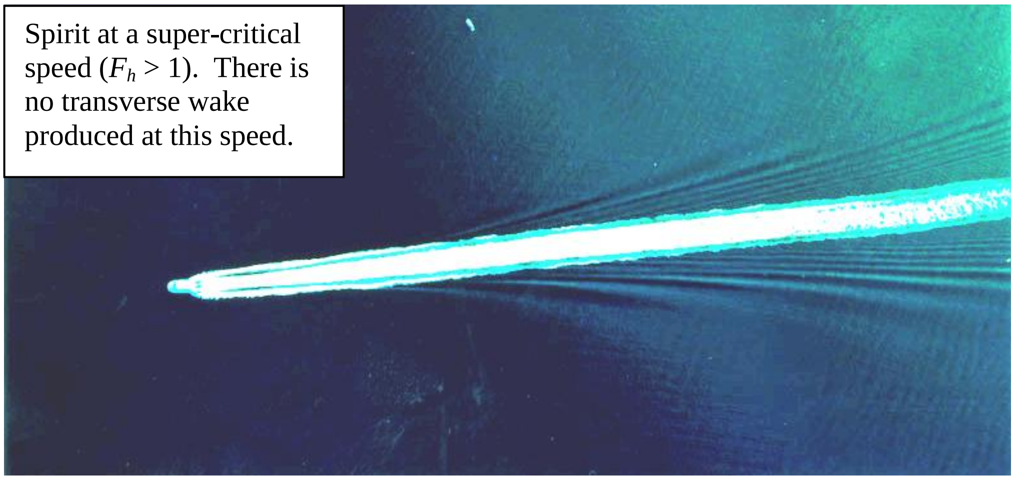

Fig. 4. Photograph of Spirit at a super-critical speed. Note only diverging wakes are present.

Fig. 5 shows the critical speed for a vessel at mean tidal level (MTL) and slack condition (no current) along the wake sensitive section of the Seattle to Bremerton Ferry route. The critical speed values vary spatially with depth and resulting F_h along the route, as well as temporally with tidal elevation. The critical speed at MTL is approximately 45 knots in the deepest portion of the waterway, and decreases to approximately 31 knots in the narrow channel between Point White and Point Glover. The range of trans-critical speeds (F_h = 0.84 -

1.15) narrows in Rich Passage as compared to the full range of trans-critical speeds along the route (Fig. 6). Fig. 6 also illustrates the variation in the trans-critical condition with tidal variation. Based on the trans-critical condition, vessel speeds between 26 knots and 36 knots can be potentially problematic for shorelines and waterfront properties depending on tidal elevation. The degree to which operation within and beyond this speed range will be problematic will depend on the wave making characteristics of the POFF vessel in operation. Potential impacts need to be assessed by conducting full-scale testing of vessels at a range of speeds and water levels.

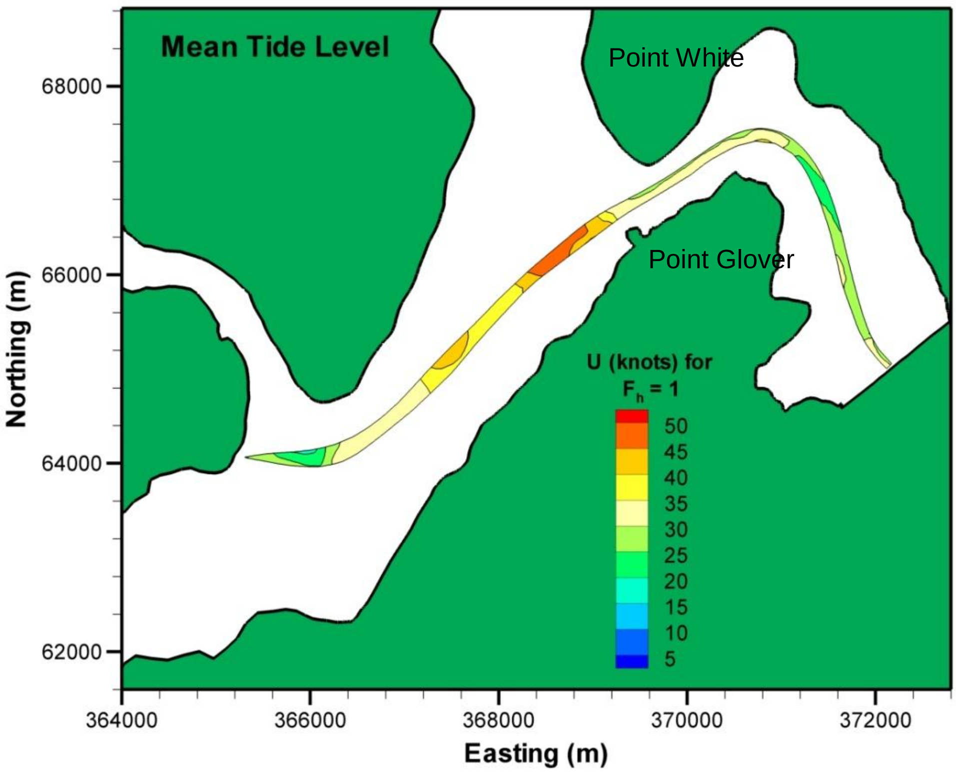

Fig. 5. Critical speeds in Rich Passage – Sinclair Inlet along the Seattle – Bremerton passenger-only ferry route at mean tide level.

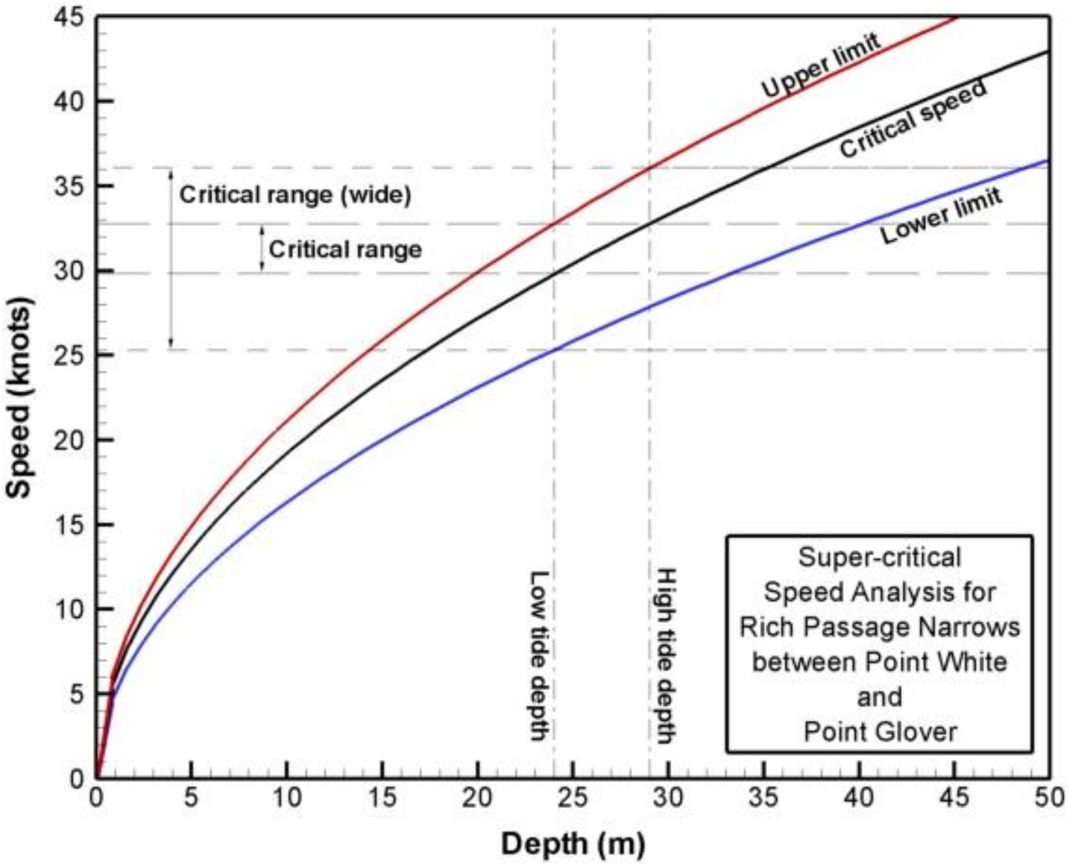

Fig. 6 Critical speeds analysis for Rich Passage Narrows between Point White and Point Glover

3. IN-SITU IMPACT STUDIES

Previous analysis of Rich Passage shorelines subjected to POFF wakes (e.g. Osborne et al., 2006) indicates that beach response is characterized by a rapid reduction in slope following the introduction of high speed ferry operations. Observations and photography revealed that mixed sand and gravel were removed from the upper foreshore and deposited near or below the low tide level; the coarse gravel armor which characterizes the beach under low energy conditions was stripped off the surface of the beach leaving a surface of finer sand exposed (Fig. 7a). The beaches exhibited no signs of recovery while subjected to POFF wakes. After just a few months of POFF operation, the beaches in several parts of the study area had lost considerable volume above the MTL and exhibited a corresponding gain in sediment volume below the MTL (Fig. 7c).

Approximately 4 years after the cessation of the previous high speed operations, beach profile monitoring was resumed under the present study. Analysis and observation indicates that on many beaches, the majority of the sediment volume above MTL had been restored to pre-POFF levels with corresponding balance below MTL (Fig. 7b and 7c).

In 2005 in-situ impact studies were conducted with M/V Spirit, a 22-m (LOA) high speed foil-assisted catamaran that was operated for a period of approximately 2 months through Rich Passage to allow direct quantitative comparison with existing displacement vessel (car ferry) operations as well as previous fast ferry operations on the route. Fig. 7c illustrates that a small volume of material was lost from above MTL and a similar volume was gained below MTL during the 2005 tests consistent with the previous fast ferry operations. Changes in sediment composition were observed on several beaches during the testing that were similar to those observed during previous POFF observations as described above.

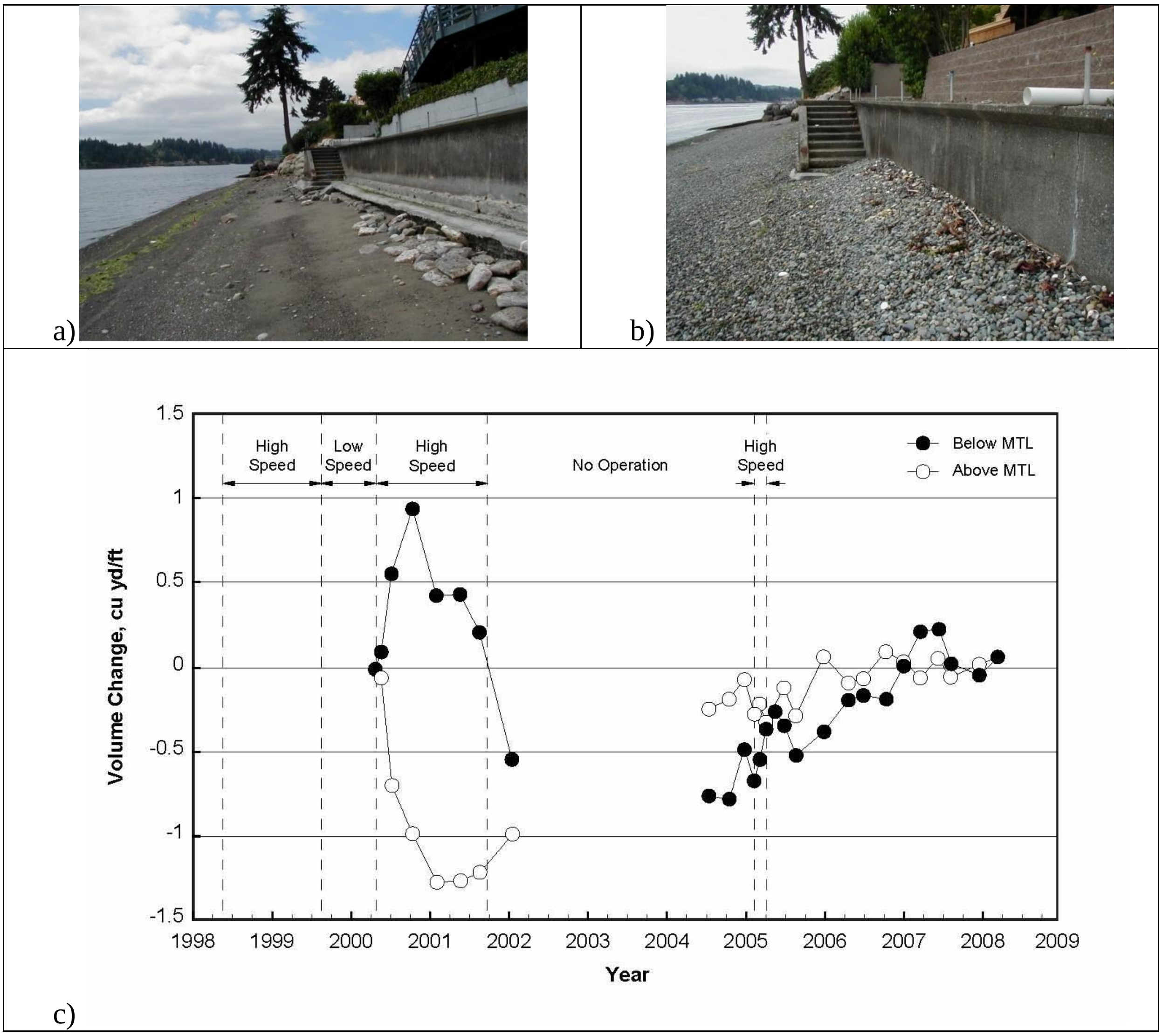

Fig. 7. Photographs of a section of beach on Point White, Bainbridge Island in Rich Passage in July 2000 following 2 months of POFF operation (a) and in August 2004 following beach recovery (b).

The results from previous operations and the in-situ trials indicate that beaches in the Rich Passage area respond differently to wakes from both high speed (critical and super-critical) operations and to slow (sub-critical) operations and ambient wind waves caused by storms. Despite small differences in wave height, the wakes from the fast POFF vessels can be significantly more energetic because their periods are longer than wakes from slower vessels. The different wave periods also result in dissimilar wave refraction patterns which produce different quantities of alongshore and across-shore sediment transport. The longer period waves associated with POFF wakes refract more as they enter shallow water and approach the shorel with their crests almost parallel to the shoreline. The shorter period wakes from smaller and slower vessels (and also wind generated waves) refract less and approach the shore at larger angles.

The longer period, more refracted POFF waves result in greater swash and backwash excursions that encourage cross-shore movement of sediment. The swash excursions are relatively symmetric encouraging net downslope movement of beach gravel and removal of sediments from the upper foreshore. In contrast, the shorter period sub-critical vessel waves are close to breaking wave height at the beach resulting in strongly asymmetric higher velocities under the wave crests. Sub-critical vessel waves encourage net shoreward movement of sediment, net accretion on the upper beach and net alongshore movement in the dominant direction of wave propagation. Recent observations of gravel transport (Curtiss et al., 2009) in Rich Passage indicate that wind generated storm waves result in predominately alongshore sediment transport (as with the sub-critical wakes) but also produce seasonal adjustments in beach slope and sediment composition (as with the super-critical wakes).

4. FULL-SCALE MEASUREMENTS WITH AN FAC DESIGN

An experimental program was designed to test the application of a foil-assisted catamaran (FAC) design that exhibits high potential for commercial application in terms of both wakes and fuel efficiency. Intensive field trials were conducted with three high speed FACs of similar design to provide detailed spatial and temporal measurements of fully spectral wake properties and vessel operating parameters over a range of operating conditions in the trans-critical and super-critical regimes. Field trial results from the foil-assisted catamaran were compared with measurements from conventional catamaran designs and a surface effect design.

In general, it was found that wake energy decreased significantly with vessel speeds above the hump speeds for each respective vessel. For example, M/V Spirit operating at speeds greater than 25 knots, showed a reduction in wake height and wake period (Fig. 8) with a corresponding decrease in wake energy.

For both FAC and surface effect vessels, vessel pitch and stern draft decreased with increasing velocity above the hump speed, with a corresponding decrease in wake energy at higher speeds. Additional field trials conducted with M/V Spirit with interceptors deployed to various settings indicated a decrease in pitch with an increase in vessel speed between 25 and 35 knots (Osborne et al., 2007). The decrease in vessel pitch corresponds to a 9 to 13 percent reduction in wake height when the interceptors were in place as compared to when they were fully retracted.

Field trial results for M/V Spirit indicate potential for optimization of the foil-assisted catamaran design through the use of a dynamically adjustable foil and interceptors. The field trial measurements were applied to the development and validation of near-field CFD (Kandasamy et al., 2009 (1,2); Peri et al., 2009) and far-field wake prediction models (MacDonald and Osborne, 2009) that provide full-scale baseline data to advance the hull design.

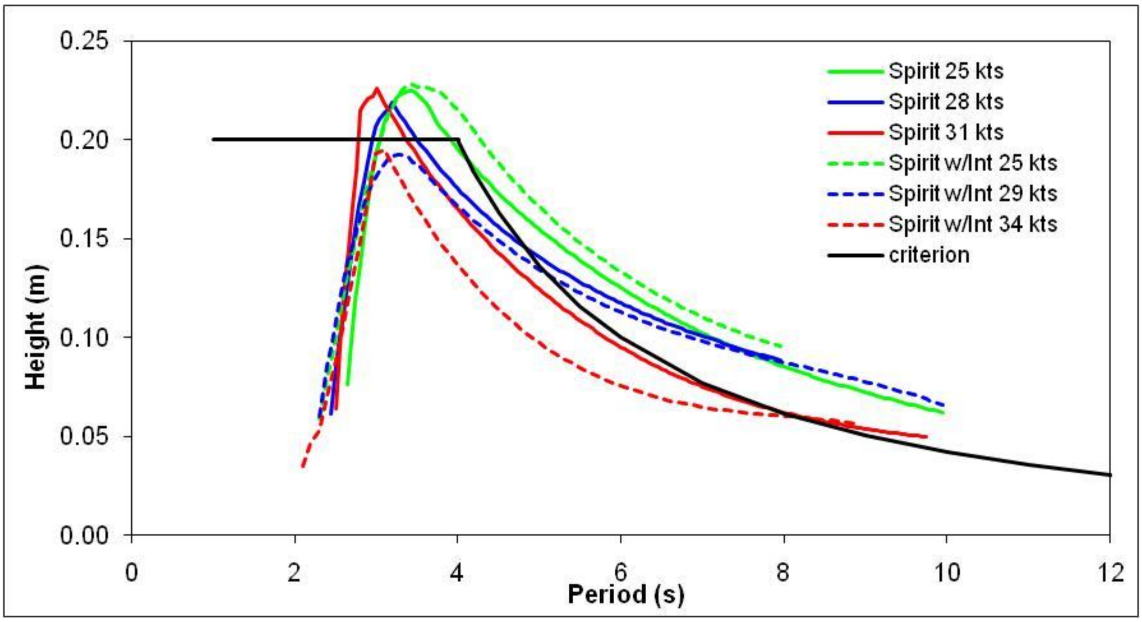

Fig. 8. Comparison of measured height spectrum for M/V Spirit operating at speeds between 25 and 35 knots, compared M/V Spirit with Interceptors and the new wake criterion.

5. A NEW WAKE CRITERION FOR RICH PASSAGE OPERATIONS

Full-scale measurements of wake parameters and vessel operating conditions are being used to establish a new comprehensive set of operational criteria to reflect the relationship between wakes from high speed vessels and the shorelines in Rich Passage. Washington State Ferries (WSF) developed a wake criterion for the selection of POFF vessels in the late 1990's on the basis of shoreline studies and wake measurements with a range of vessels available at the time. The criterion was to keep the largest wave in a wake to less than or equal to a wave height of 0.28 m with an energy density of not more than 2450 J/m as measured in deep water at a distance of 300 m from the vessel sailing line.

Fig. 9 shows a comparison of average wake heights for a typical range of wave periods based on full scale measurements from a number of vessels at speeds between 30 and 40 knots. The data have been adjusted to a common distance of 300 m from sailing line by taking into account the change in wave height with distance from sailing line. A distance decay factor with a dependence on speed, wave period and water depth was applied. Fig. 9 shows a similar comparison of average wake energy for the same data. Wake energy is a function of both height and period. The results show that wake height maximum for the *Chinook*-class vessels (POFF historically operated through Rich Passage) occurs at a wave period of 5 seconds whereas the height maximum for the smaller FACs occurs at approximately 3 seconds. This reflects the larger size of the *Chinook* relative to other vessels in the comparison. In contrast, wake energy for the *Chinook*-class vessels continues to increase as wake period increases and actually exceeds the WSF wake criterion for periods greater than approximately 5 seconds. In comparison, the wake energy for the FACs peaks at approximately 3 seconds and decreases with increasing period.

Recommended target wake height and energy levels for a new POFF wake criterion are also shown in Fig. 9. The new wake height criterion is specified as follows:

$$\begin{bmatrix} T_j \le 3.5 : H_j \le 0.20 \\ T_j > 3.5 : H_j \le 1.16T^{-1.4} \end{bmatrix} \quad (4)$$

Where T_j is the j^{th} wave period in a wake train in seconds and H_j is the average wake height for waves at the corresponding j^{th} period of the wake in meters measured at 300 m from the sailing line. Although similar in general form to the WSF criterion and the "wash rule" developed by the Danish Maritime Authority (DMA, 1997; see also Croad and Parnell, 2002), this new criterion differs fundamentally from previous WSF criteria and also the "wash rule" developed by the DMA. The latter refer only to the maximum (largest) wave in a high speed wake train whereas, the new Rich Passage criterion applies to all waves in a wake train, recognizing that long period waves present in the wake train may have amplitudes much smaller than the largest wave, even in relatively shallow water, but nonetheless be capable of damage to beaches or structures. In addition to full spectral wake characteristics, the new criteria for this route will also include a limit on the number of trips per day, speed restrictions for extreme water levels, and recommended sailing lines that will be based on in-situ impact studies with new vessels prior to them being put into service.

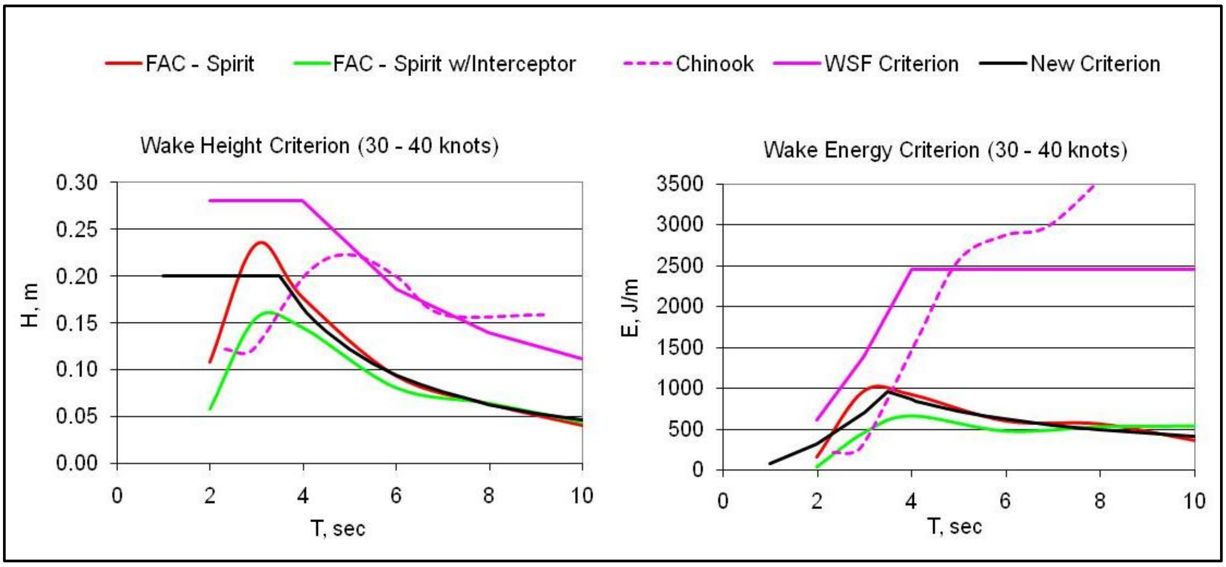

Fig. 9. Comparison of measured height and calculated energy spectrum for foil-assisted catamarans and POFF operating at 30 to 40 knots, compared to previous wake height criterion set by WSF and new wake performance criterion.

4. SUMMARY AND CONCLUSIONS

Beaches in the Rich Passage area respond differently to wakes from both high speed (critical and super-critical) operations and slow (sub-critical) operations. Despite small differences in wave height, the wakes from fast vessels can be significantly more energetic because their periods are longer than wakes from slower vessels. The longer waves result in greater swash and backwash and subsequently remove sediments from the upper foreshore while the shorter period wakes from smaller and slower vessels result in net accretion on the upper beach.

Results indicate that a foil-assisted catamaran design optimized for low wake operations has the potential to operate at trans-critical and super-critical speeds with significantly reduced impact compared with a conventional catamaran that formerly operated on the Seattle-Bremerton route.

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