RESPONSE OF MIXED SEDIMENT BEACHES TO WAKE WASH FROM PASSENGER ONLY FAST FERRIES: RICH PASSAGE, WASHINGTON

Philip D. Osborne[1], Neil J. MacDonald[1], and William J Reynolds[2]

The Rich Passage Passenger Only Fast Ferry Study is investigating the feasibility of restoring passenger only fast ferry (POFF) service between Seattle and Bremerton in Puget Sound, Washington. The mixed sediment beaches respond to POFF and non-POFF wakes, large water level variations and currents, and wind waves. Beach response does not follow the high-energy coarse-grained beach model; rather, it is more consistent with the response expected for a low-energy mixed beach backed by a seawall. Despite small differences in wave height, POFF wakes are significantly more energetic because their periods are longer than wakes from slower and smaller vessels. The longer POFF waves result in greater swash and backwash excursion. Beach profile response to POFF operation is rapid, occurring over an interval of several weeks. POFF wakes mobilize and remove sand and coarse-grained sediments from the upper foreshore and deposit it on the middle and lower foreshore or move it alongshore. Smaller and shorter period wake wash from smaller and slower vessels result in net accretion of sand and gravel on the upper beach. The situation is further complicated by the apparent differential rates of erosion for gravel as opposed to sand and by the prevalence of alongshore transport resulting from wake wash approaching the shore at an angle. Gravel and cobble particles, once set in motion by turbulence and shear under breaking waves, are rolled preferentially downslope on the steep (1:5 to 1:7) beach face. Fines are removed from the coarse matrix, possibly by exfiltration at low tide. During recovery phase following slow-down or cessation of POFF operations, the waves do not have sufficient energy to transport the largest gravels and cobble back upslope. Therefore, an accumulation of coarse sediment occurs at the toe of the slope while finer gravel and sand accumulates higher on the beach.

INTRODUCTION

The Rich Passage Passenger Only Fast Ferry Study was initiated to quantify shoreline impacts from high speed Passenger Only Fast Ferry (POFF) operations. The shores of Rich Passage, WA are comprised of several discrete littoral cells ranging from tens of meters to kilometers in length. The sediment distribution in these cells is complex, with beaches that consist either of a hard bottom, sand, gravel, cobble, shell hash, or some combination therein. Furthermore, these beaches are exposed to wake wash from POFF operations as well as other vessels, large water level variations and currents, and wind waves. The combination of external forces and range of sediment sizes influence the

[1] Pacific International Engineering, PLLC, PO Box 1599, 123 Second Ave S. Edmonds, WA, 98177, USA; philo@piengr.com ; neilm@piengr.com
[2] Cypress Inc., 3310 Comanche Drive, Mount Vernon, WA 98273, USA; wjreynolds@cypressltd.com

hydraulics and sediment transport processes in the nearshore. Due to the complexity of the environment and the lack of information regarding wakes and shore processes in the area, the study undertakes a multidisciplinary approach involving numerical modeling, physical and biological monitoring, and coastal engineering. This paper presents an analysis of the response of the mixed (sand, gravel, and cobble) beaches in Rich Passage utilizing both field measurements and the development and application of numerical models.

Background

For over two decades, there has been considerable interest in providing POFF service on central Puget Sound between the cities of Seattle and Bremerton (Figure 1). POFF service may offer considerable savings in commuting time over the conventional car ferry service offered by Washington State Ferries (WSF). The one-way distance between Seattle and Bremerton along the ferry route is approximately 14 nautical miles; a one-way trip at a speed of 35 knots would take approximately half an hour, whereas the conventional car ferry service offered by WSF operates at half that speed and takes approximately one hour to make the trip.

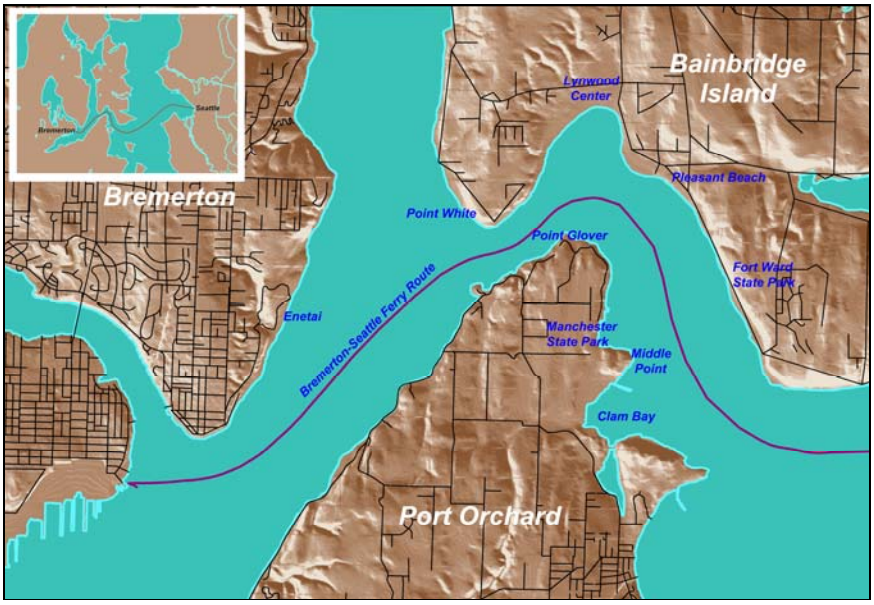

Figure 1. Seattle-Bremerton ferry route and Rich Passage study area

Despite the interest in POFF service and its potential benefits to commuters, a major difficulty arises owing to the need for waterborne traffic between the cities to pass through Rich Passage, a narrow body of water separating the south end of Bainbridge Island from the mainland portion of Kitsap Peninsula at Port Orchard (see Figure 1). Rich Passage is no more than 600 m wide at its narrowest point between Point White and Point Glover. In the past, Rich Passage property owners have filed complaints and a lawsuit alleging bulkhead damage, beach erosion, and biological degradation caused by POFF wakes. In October 2001, the State Attorney General reached a settlement with Rich Passage property owners concerning damage to property associated with POFF operation through Rich Passage and agreed to maintain speeds of passenger ferries at less than 16 knots through Rich Passage. In February 2003, WSF suspended POFF service on the Seattle-Bremerton route due to budget shortfalls. The aim of the present study is to quantify shoreline impacts from POFF operations and assess the feasibility of developing a new POFF service that will meet the commuting needs of Kitsap County, while not adversely affecting waterfront properties along the route.

METHODS

Measurements collected in Rich Passage and analyzed in the study include open water wake trial data, nearshore wake wash and wind wave time series, samples of beach sediments, multiple surveys of bathymetry and topography, time series of tidal currents and water levels and direct measurements of gravel and cobble transport. Wake time series from several high-speed vessels, including commercially operated POFFs and a foil-assisted catamaran being used as a research vessel in the present study, were extracted from water surface elevation measurements made in-situ in Rich Passage. Routes of POFF and non-POFF vessels transiting Rich Passage were recorded with Global Positioning Systems (GPS) to correlate vessel transits with wake time series and to determine vessel speeds and positions relative to gauges. Additional details of the measurements are provided in Osborne and MacDonald (2005).

Computer model application in the study includes a tidal circulation model, a wave climatology model, a beach profile evolution model, and a new wake model for high speed vessels (MacDonald, 2005; Osborne and MacDonald, 2005). The wake model predicts both the generation wakes and transformation by tidal currents and bathymetry from a vessel to the shore. Wake data from trials of POFF vessels were used for development of the model, which has been successfully validated against in-situ measurements. The models are being used to study the spatial variation in shore impacts from alternative hulls and to investigate the vulnerability of beaches in the study area to impact from POFF operations.

Beach Profile Monitoring

Figure 2 shows the location of beach profiles that are monitored as part of the Rich Passage Study. Sites 1 through 13 have were monitored during the previous POFF operations by WSF between April-May 2000 and February 2002 (RPWAST, 2001, 2002). Monitoring on these, and the additional sites shown in Figure 2, was resumed as part of the present study in August 2004. Profiles are surveyed approximately quarterly with a survey grade Trimble 5800 RTK GPS system. Survey transects extend from the top of the bulkhead or backbeach area to approximately mean lower low water (mllw). This paper will focus on beach profile, and sediment transport measurements made on the southeastern shore of Point White, Bainbridge Island at sites 3 through 6 (Figures 1 and 2).

Figure 2. Location of beach profile monitoring sites

Gravel Transport Measurements

Gravel transport is measured directly in the study using Radio Frequency Identification technology (RFID) to detect Passive Integrated Transponder (PIT) tags inserted in beach gravels (Allan et al., 2006; Nichols, 2004). PIT tags are glass encapsulated transponders that are activated when an antenna passes near them. Each tag is characterized by its own unique identification number. The tags are sealed within the cobbles, minimizing any effect on the hydrodynamic character of the particles. The RFID system consists of three components, the transponder tags, a reader/control module and an antenna.

The gravel tracers were made from sediment samples acquired by sampling the surface layer of beach sediment. The tracers were chosen to match a representative sample of four size classes found on the beach: (passing sieve size) 16 mm, 22.6 mm, 32 mm, and 45 mm. Because of the size constraints of the RFID tags, the size distribution of the tracers is weighted towards larger particles than those in the representative beach sample. Each tracer set contains 48 particles with approximately the same size and shape indices. Two tracer sets were deployed at sites separated by approximately 150 m on Point White

The positions of the gravel tracers were recorded using a Trimble 5800 RTK-GPS system with horizontal and vertical tolerances set at 0.03 m. At times, accuracies decreased to 0.1 m because of poor GPS satellite reception. Tracer recovery has been consistently above 90% throughout the deployment, which has lasted more than 60 days.

Wake Modeling

PI Engineering developed the Lagrangian Super Critical Vessel (LSV) model (MacDonald, 2005) to predict both the generation and the transformation of wakes from high speed vessels, such as power boats and POFFs. The LSV wake model provides a realistic and accurate estimation of the wake train duration and amplitude distribution in space and time. The LSV model has the following capabilities:

- Vessel-specific generation of sub- and super-critical wakes;
- variable vessel routing and speed;
- wake transformation, including the effects of:
  - current refraction;
  - depth refraction;
  - shoaling;
  - breaking;
  - wake train dispersion.
- efficient solution for large areas and numerous simulations.

The LSV wake model is particularly useful for producing spatial distributions of directional wake power, which can be analyzed to estimate sediment transport. This allows hot spots to be identified and can assist in investigating the spatial variations in shore impacts and trends in sediment transport that may be produced by alternative POFF operation scenarios.

RESULTS

Representative Wake Time Series for POFF and non-POFF operations

The wake train produced by the passage of a vessel is represented by a series of individual waves. The characteristics of the wake are related to the depth Froude number:

$$F_d = \frac{V}{\sqrt{gd}}$$

where g is the gravitational constant, d is the depth of water and V is the speed of the vessel relative to the water.

The differences between super-critical and sub-critical vessel wakes are illustrated in Figure 3 from Osborne and MacDonald (2005). Each half of the figure contains three plots; the upper plots show the free surface elevation and the wake height determined from a zero-crossing analysis; the middle plots show the wake period determined from a zero-crossing analysis, and; the lower plots show the wake energy spectrum in the frequency domain. In the left half of Figure 3, a high-speed vessel is operating at its super-critical design speed. The wake period shows a smooth, steady decay with time. The wave energy spectrum shows a series of peaks or energy concentration at a number of frequencies. In the right half of Figure 3, the same vessel is sailing at a sub-critical speed. Although there are groups in the wave train, the wake period is constant and the corresponding wave energy spectrum is monochromatic. In summary, if the vessel is in a sub-critical regime (i.e. $F_d < 1$), then the wake is monochromatic; if the boat is super-critical, then the wake will contain energy over a range of frequencies.

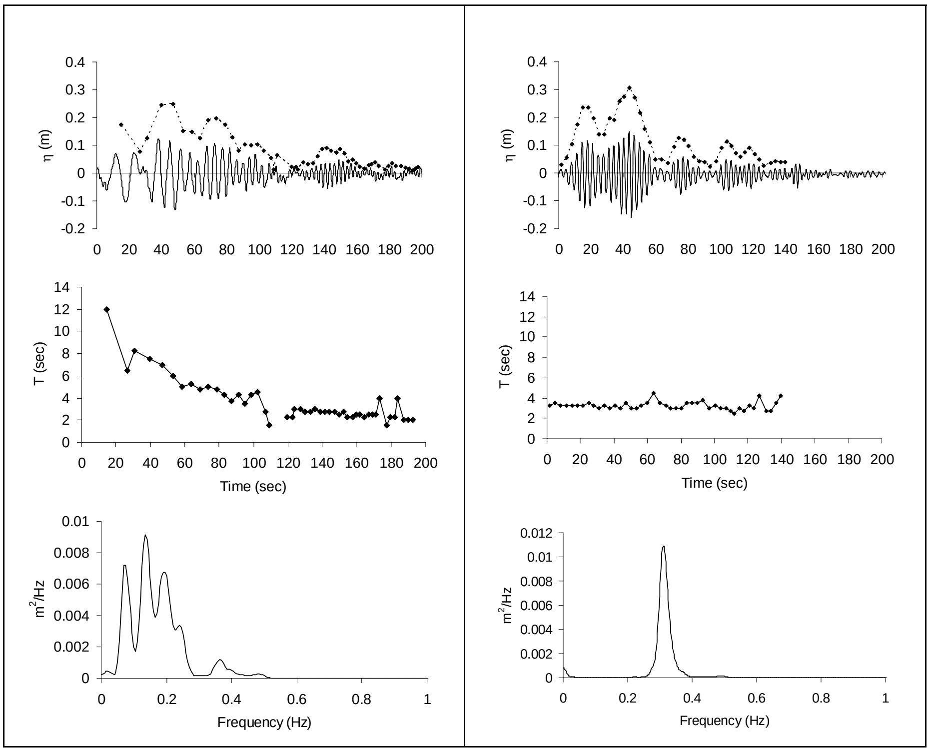

Figure 3. Typical results for a high speed vessel at super-critical speed (left), and the same vessel at sub-critical speed (right) (Top: surface elevation and wake height; Middle: wake period; Bottom: energy spectra).

Beach response to POFF and non-POFF operations

Figure 4 shows the beach volume changes above and below the mean tide level (MTL) at transect 4B determined from beach profile measurements. Site 4B is representative of the patterns of beach change that have occurred at sites on Point White since May 2000. The beach along Point White exhibited flattening (erosion above the MTL and accretion below) in response to WSF-class POFF operations between May 2000 and October 2001. The volume of sediment lost from the area above MTL is approximately equal to the volume gained below MTL indicating that much of the response is accounted for by cross-shore redistribution of sediment. However, the timing of the response was progressively delayed at positions with increasing distance northeast of the end of Point White indicating a significant alongshore component to the beach response. These observations are confirmed by photographic and anecdotal observations (RPWAST, 2002).

The majority of the beach response to POFF operation occurred within a few weeks following the start of service. The beaches then approximately stabilized after a few months of exposure to POFF wakes. As of 2004, the beach volume above the MTL was approximately at the same level as May 2000 while the volume below MTL is slightly lower than the May 2000 level, consistent with a slight overall steepening of the beach profile. Although a seasonal fluctuation of approximately +/- 0.5 cy/ft of beach is evident, there was no measurable response to the POFF trials conducted with the foil-assisted catamaran in 2005. The 2005 data indicate that the beach steepening (return to pre-POFF condition) has occurred in response to the prevailing wake and wind wave climate since the cessation of WSF-POFF operations.

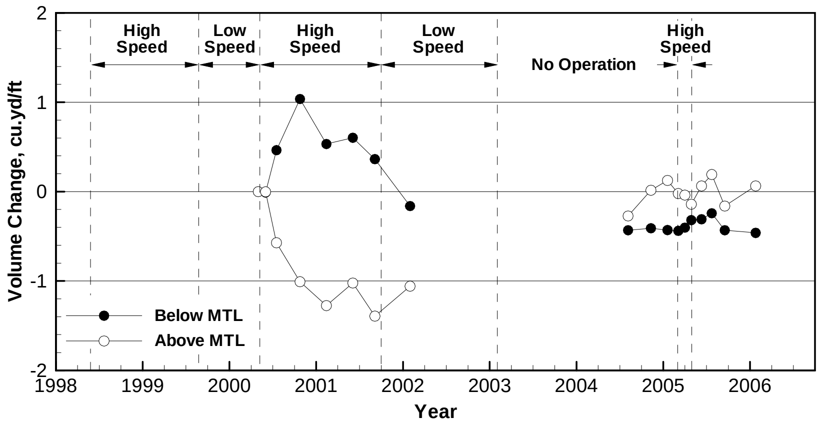

Figure 4. Beach volume changes above and below the mean tide level on Point White relative to May 2000 during intervals of high speed and low speed POFF operations.

Gravel transport under a non-POFF wake climate

Figure 5 shows the centroid position of particle tracers by size class for a 64-day interval of monitoring. The centroid position is the spatially averaged position of all particles in each size class. The tracer centroid paths illustrate the response of the beach gravel to the prevailing summer wake and wave climate at this location. The wake climate was dominated by wakes from car ferries and recreational vessels during this interval and no major wind wave events were observed; in other words, the measurements are representative of the existing non-POFF wake wave climate and tidal currents. These short term measurements reveal distinct sediment sorting patterns by size class. The smaller particles (passing sieve opening 16 mm) have moved to higher elevations on the beach (closer to the bulkhead) while the large particles (passing 45 mm) have moved lower on the beach (further from the bulkhead).

This sorting pattern is consistent with the native grain size distribution observed on the beach. The sorting patterns were established within a few days after deployment and particle centroid positions have remained at essentially the same cross-shore location thereafter. A relatively steady net transport to the north east has occurred during this interval. The net transport is in the opposite direction to the residual tidal current at this location.

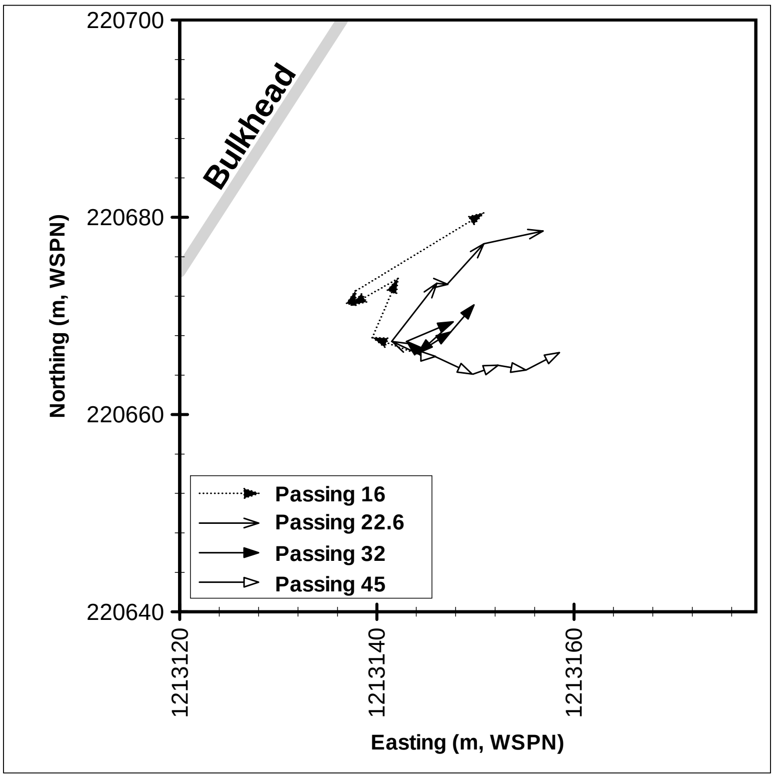

Figure 5. Plan view of centroid positions of particle tracers in Group 2 by size class between Day 1 and day 64 (August 1 – October 3, 2006); the gray hachured area in the upper right is the position of the bulkhead at the top of the foreshore.

LSV Model Application

The primary wake impact assessment tool to be used in the study is the LSV model. Its results can be used to provide input to secondary tools (e.g. profile response models), if required. At present, the model's results have been analyzed to determine indicators of potential response. One of the most directly relevant indicators is wake power, P. This quantity is determined from the equation:

$$P = \frac{1}{2} c_g E \sin \alpha_b$$

where α_b is the angle between the wake propagation direction and the local shore normal. This quantity is proportional to longshore littoral transport.

To illustrate the potential applications for this approach, LSV model predictions of longshore wave power at a location near the gravel transport monitoring site and the profile volumetric change measurements are shown in Figure 6. These preliminary simulations are produced using average speed and route data from numerous GPS position measurements of POFFs taken between 1999 and 2002. The simulations are for three representative POFFs: *M/V Snohomish, M/V Bravest,* and *M/V Condor Express*. Each point in Figure 6 represents the cumulative power from an individual wake train at breaking for a high water slack condition. The sign of the wave power in Figure 6 indicates the direction, with positive indicating a northeastward direction. It is clear from the results that *Snohomish* produces the largest relative impact at the shore, with *Bravest* somewhat smaller. *Condor Express* produces the least impact.

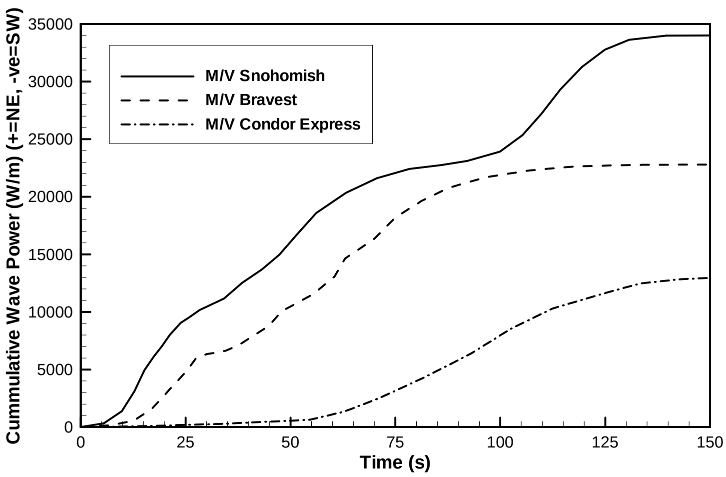

Figure 6 . Cumulative alongshore wave power from the wake of three POFFs (Bremerton to Seattle, high water slack)

The differences on the return trip (Seattle to Bremerton) are more extreme (Figure 7). *Snohomish* and *Bravest* both show northeastward forcing again, while *Condor Express* produces almost no net impact. This result for *Condor Express* is believed to be caused by wake breaking at the shore with almost a shore-normal angle.

DISCUSSION AND CONCLUSIONS

The mixed sediment beaches along the Seattle-Bremerton ferry route exhibit a variable response to high speed POFF and non-POFF operations. A POFF dominated wake climate results in beach flattening, while a non-POFF dominated climate results in steepening of the beach foreshore. This variable response is related to the difference in the wake signatures for POFF and non-POFF operations exemplified in Figure 3.

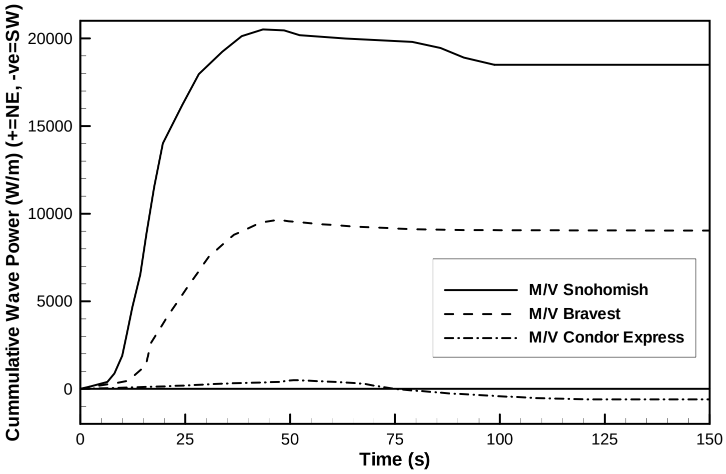

Figure 7. Cumulative alongshore wave power from the wake of three POFFs (Seattle to Bremerton, high water slack)

Despite small differences in wave height, POFF wakes can be significantly more energetic because their periods are longer than wakes from slower and smaller vessels. The longer POFF waves result in greater swash and backwash excursion. POFF wakes mobilize and remove sand and coarse-grained sediments from the upper foreshore and deposit it on the middle and lower foreshore or move it alongshore. The smaller and shorter period wake wash from smaller vessels (e.g. recreational vessels) or slower speed vessels (e.g. car ferries) results in accretion of sand and gravel on the upper beach, steepening of the profile, and alongshore transport.

Beach response to POFFs is further complicated by the differential rates of erosion for gravel as opposed to sand, the presence of bulkheads and seawalls on the foreshore and by the prevalence of alongshore transport resulting from wake wash approaching the shore at an angle. Gravel and cobble particles, once set in motion by turbulence and shear under breaking waves, are rolled preferentially downslope on the steep (1:5 to 1:7) beach face. Fines are removed from the coarse matrix, possibly by exfiltration at low tide. During the recovery phase following slow-down or cessation of POFF operations, the waves do not have sufficient energy to transport the largest gravels and cobble back upslope. Therefore, a reverse grading of the surface sediment is observed on these beaches under a non-POFF dominated wake climate, with coarser sediment accumulating at the toe of the slope and finer gravel occurring at higher elevations. Observations of gravel tracer sorting under a non-POFF wake dominated climate are consistent with these observations and interpretations. The presence of bulkheads on the foreshore may interfere with the uprush of wakes thereby inhibiting the formation of a coarse berm at the top of the foreshore under POFF and non-POFF regimes. The observed beach response exhibits several similar characteristics to that described for low-energy mixed beaches backed by seawalls (e.g. Quick and Dyksterhuis, 1994; Lawrence and Chadwick, 2006).

Application of a numerical wake prediction model produces a net alongshore transport potential under wakes that is consistent in direction with measurements of gravel transport under a non-POFF regime. Additional work is needed to acquire data from a POFF wake regime and under varying wind wave conditions to provide data for calibrating a quantitative model. Simulations with a number of different POFFs indicate a wide range in transport potential resulting from varying wake wash signatures and energy. Future work will examine the contributions of POFF, non-POFF wakes, and wind wave climate to sediment transport potential in order to quantify relative impacts to beach response on a system-wide basis. A successful future POFF operation will need to achieve cumulative wake energies and transport potentials that are sufficiently low to avoid dominating the non-POFF and seasonal wind-wave beach response.

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