Gravel transport and morphological response on a supply-limited beach, Point White, Bainbridge Island

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Abstract
Direct measurements and observations of coarse sediment (gravel) transport, beach morphological change, scour and accretion patterns, beach sediment characteristics, and forcing mechanisms have been obtained over a number of time intervals from 2000 to present from a mixed sand and gravel (MSG) beach on Bainbridge Island, Puget Sound, WA. The beach is backed by bulkheads and seawall structures along the full length of the study site (approximately 1 km) and has been exposed to wind waves, vessel-generated waves from both passenger-only fast ferries (POFF) and conventional vessels, and tidal currents. A series of studies, summarized in this paper, have quantified the relative role of the different forcing mechanisms and determined the corresponding time scales of sediment transport, morphological response, and scour.

This paper provides a synthesis of the long term observations on Point White including an overview of gravel transport measurement obtained over a 14-month interval and measurements and observations of beach morphological response over an 8-year interval to illustrate the relationships between sediments and supply, morphology, processes, and forcing on a typical Puget Sound beach that has been armored by bulkheads and subject to variable wake and wave climate for several decades. The observations indicate differences in the sediment transport regime and morphology response between storm and non-storm conditions and between POFF and non-POFF vessel operations. Storm intervals (typically November through April) are characterized by an alongshore transport rate of 6 to 90 times the rate during non-storm intervals as a result of offshore transport of coarse sediment and the exposure of sand on a flat upper beach slope induced by wind waves. Non-storm intervals (typically May through October) are characterized by minimal alongshore transport (resulting from contributions by vessel wakes and tidal currents), and weak onshore transport which leads to gravel berm formation on the upper beach and steepening. 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 which often interact with structures. Beach profile response to POFF operation is rapid, occurring over an interval of several weeks. Large POFF wakes mobilize and remove sand and coarse-grained sediments from the upper foreshore and deposit it on the middle and lower foreshore and shallow sub-tidal areas. Smaller and shorter period wakes from smaller and slower vessels (such as car ferries) result in net accretion of sand and gravel on the upper beach over periods of months to years. The long term observations of beach morphology change, transport patterns, and sediment size and volume variations that include a downdrift fining and thinning, are consistent with the observation that the MSG beach at Point White is supply limited and undergoing long term passive erosion most likely as a result of construction of bulkheads along the length of the study area.

Introduction

Accurate predictions of sediment transport and beach response are essential for making well-informed decisions regarding the design, permitting, and placement of both engineered structures and beach nourishment projects in the coastal environment. Improper design of structures may lead to long term erosion of the adjacent or down-drift beaches and subsequent impacts to sensitive beach habitat.

Understanding the seasonal and longer-term dynamics of mixed sand and gravel (MSG) beaches is limited as compared to sandy beaches by the lack of long term data of beach response and forcing and the limited predictive capability of numerical models. In particular, there is a lack of information documenting the impacts (long term and short term) of seawalls and bulkheads on MSG beaches.

The operation of ferries in the fetch restricted coastal system of Rich Passage in Puget Sound, WA, USA has provided the unique opportunity to study the dynamics of a MSG beach with bulkhead structures that is exposed to a wide range of wakes, wind waves, and tidal currents. During previous passenger only fast ferry (POFF) operations from 1999 to 2002 the upper foreshore of beaches in Rich Passage were eroded and the slopes were reduced. It is hypothesized that the longer period POFF wakes caused the flattening and erosion of the upper foreshore, whereas car ferries have resulted in beach steepening and accretion of the foreshore (Osborne et al., 2007). The presence of bulkheads or seawalls is also hypothesized to have had a long term (decadal) impact on sediment supply and thereby contributed to passive erosion in the study area.

The goals of the present study were to resolve seasonal patterns of sediment transport and morphology change on a MSG beach that is backed by bulkheads, quantify the relative role of the different forcing mechanisms (wakes, waves, and tidal currents), and apply the measurements to validation of a system of integrated numerical models that can be used for wake impact assessment in the study area. In this paper, we provide an overview of the results of direct measurements, and observations of coarse sediment (gravel) transport and beach morphological change that were obtained over a number of time intervals from 2000 to present from a MSG beach on Bainbridge Island, Puget Sound, WA and comment on the relationships with beach sediment characteristics, and forcing mechanisms. The interested reader is referred to papers by Curtiss et al., 2009; Osborne et al., 2007; and Osborne and MacDonald, 2007 for more detailed discussion of the measurements and modeling.

Study Area and Sediment Characterization

The study site (Figure 1) is an approximately 500 m length of MSG beach in Puget Sound on the east shore of Point White, at the southern end of Bainbridge Island, Washington, USA. Point White lies at the western end of Rich Passage, a narrow channel that provides the most direct vessel route between downtown Seattle and the city of Bremerton, WA. The beaches are backed by bulkheads and revetments of varying type and condition along the length of the study area. Data including wind, wave, current measurements, sediment samples, and gravel tracer measurements were collected at two separate sites which are denoted here as PWA and PWB (see Curtiss et al., 2009 for details).

Beach and inter-tidal deposits at Point White are a thin layer of sediment eroded into a beach platform composed of Holocene age Vashon till (Haugerud, 2005). The mobile sediment layer is the result of reworking of coastal exposures of till, outwash sediments, and glaciomarine and glaciolacustrine deposits (Finlayson, 2006). The beach foreshore along Point White is generally steep (1:5 to 1:7), with a 20 to 30 m wide strip of beach gravel (pebble and cobble) overlying mixed sand and gravel or consolidated till. The beach unconsolidated layer varies in thickness from a few cm up to 2 m in places on the upper foreshore and at the toe of bulkheads. The unconsolidated layer is generally thicker at PWB than at PWA; the beach to the south of PWA is a single grain thickness of gravel over till. The gravel layer varies from 0.5m to as thin as a single grain thickness of gravel armor on the lower foreshore. The cross-shore sorting is related to the relationship between swash energy, tide, and gravity/slope effects. The sediments were characterized by pebble counts of the surface layer and sieving samples from the upper 30 cm. The median grain size based on the pebble count is 22.5 mm at PWA and 17.0 mm at PWB. The median grain size for the entire sediment mixture based on sieving is 16.0mm at PWA and 11.0 mm at PWB. A unique feature of the beach is the median size of the gravel, which increases with decreasing elevation on the beach as also observed by Nordstrom and Jackson (1993) on a low energy estuarine beach.

Gravel Tracer Measurements

Direct measurements of pebble and cobble (gravel) transport were obtained at Point White using Radio Frequency Identification (RFID) Passive Integrated Transponder (PIT) particle tracking methods (Allan et al., 2006). Tracer particles were made from samples of beach surface sediment chosen to match the size and shape of the native distributions as closely as possible but constrained by the minimum size of the PIT tags (12 mm). Sets of 48 tracers were deployed in random grids with 30 cm spacing about the mean tide level at PWA and PWB from 1 August 2006 through 5 October 2007. A tracer survey consisted of finding the tracers with the RF control module and recording their positions with the RTK-GPS, leaving the tracers undisturbed. The RFID tracking methodology provided high recovery rates of the tracers. In general, the recovery was above 80% (min. of 73%) throughout the study. Lowest recovery occurred during winter months when storms resulted in higher burial rates, offshore transport, and higher tidal elevations during surveys.

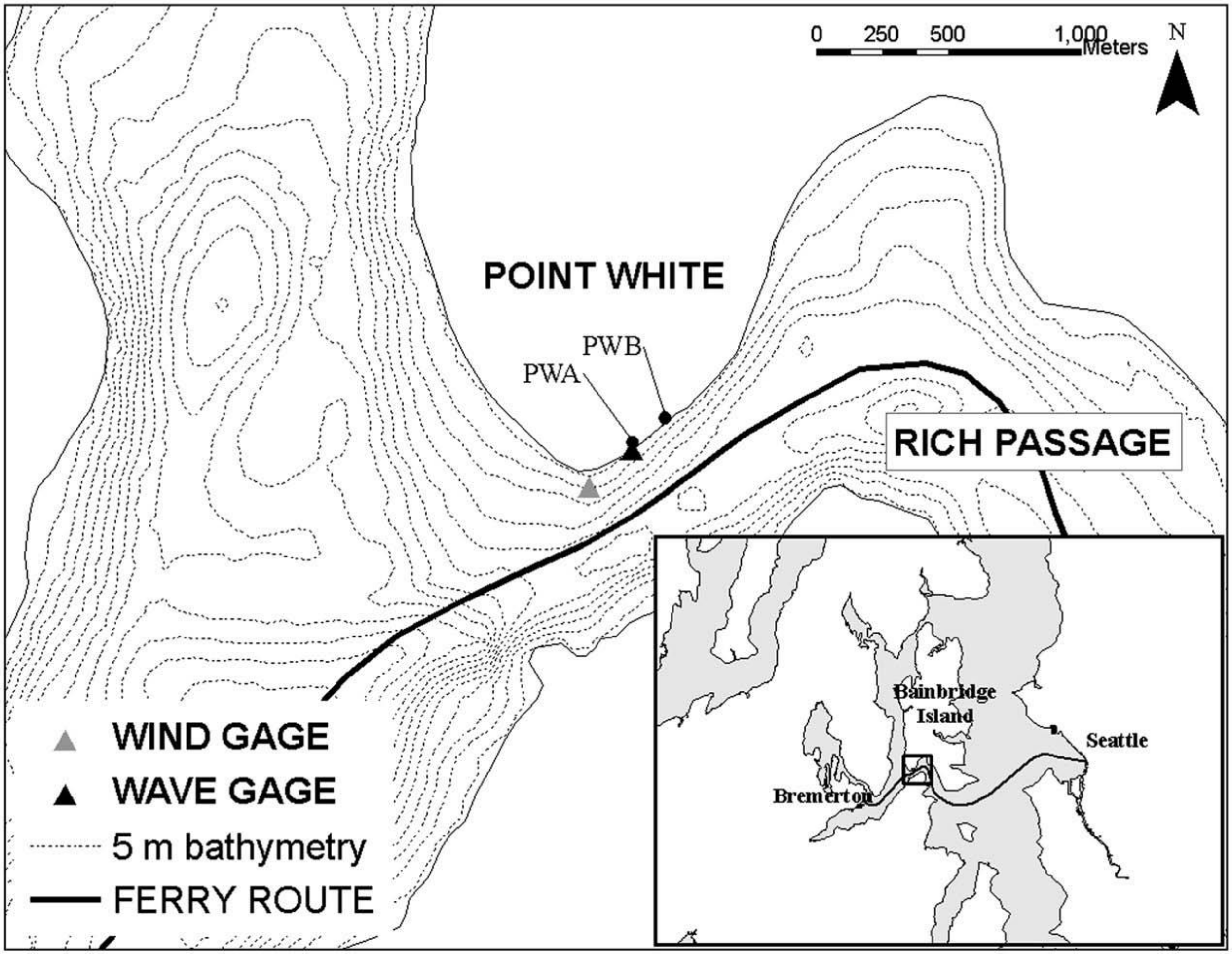

Figure 1. Study area and the location of tracer deployments, wind and wave measurements.

The particle tracking data were analyzed to determine the magnitude of alongshore and cross-shore transport between survey periods as well as any dominant patterns based on particle size or location on the beach. Figure 2 is a map of the tracer distributions on 1 August 2006 and 5 October 2007 and of the centroid of the tracers through time. The most noticeable feature is the amplified alongshore movement of the tracers to the northeast at both sites between November 2006 and the end of December 2006. Tracers at PWA move alongshore at a rate of approximately 0.065 m/day between April and November, while at PWB the rate of movement alongshore is 0.005 m/day in the same interval. The daily transport rate at PWA increases by a factor of 6 in the period between November and January. At PWB the alongshore transport rate increases by a factor of 90 during the month of December. The transport during December is largely a result of the 10-yr storm that occurred on 13–14 December 2006. The magnitude of alongshore movement in December is similar at both sites. However, the magnitude of alongshore movement during the non-storm intervals is higher at PWA and is possibly explained by site specific differences in exposure to wind waves and vessel wakes. The patterns of dispersal in relation to forcing are discussed in more detail in Curtiss et al., 2009.

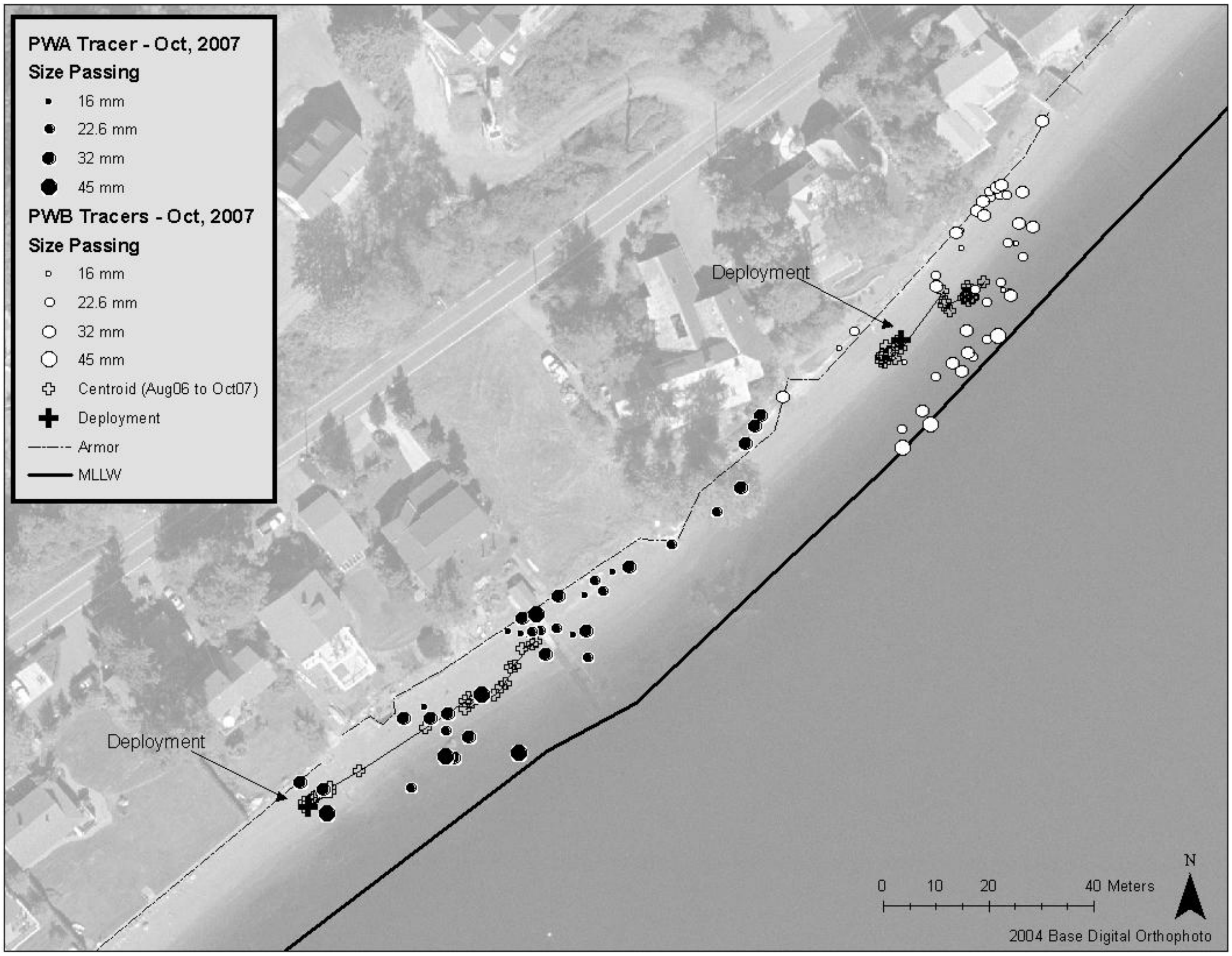

Figure 2. Spatial map of tracer distributions at the final survey in October 2007 and the position of tracer centroids through time between August 2006 and October 2007 at Point White.

Beach Morphology Change

Figures 3 and 4 show the intervals of passenger fast ferry operations in Rich Passage and the volumetric change to the upper and lower profile (above and below mean tide level) from the last eight years at both PWA and PWB relative to May 2000. The introduction of high speed ferries in 2000 initially resulted in erosion from the upper foreshore and accretion on the lower foreshore. The lower foreshore eventually eroded as well at both sites. The profile at PWA indicates a gradual erosion trend since 2004; erosion during the winter of 2008 was particularly severe. Between 2004 and the time of the gravel tracer study the entire beach at PWB was slowly accreting sediment such that the beach recovered to the volumes present in May 2000. Erosion of the entire profile occurred during the winter of 2008. It is evident that the winter erosion caused by wind waves in this area is equivalent in magnitude to the erosion caused by the fast ferries. The winter storm erosion appears to remove sediment from both the upper and lower profile (profile retreat) rather than re-distribute the sediment across shore (profile flattening or steepening).

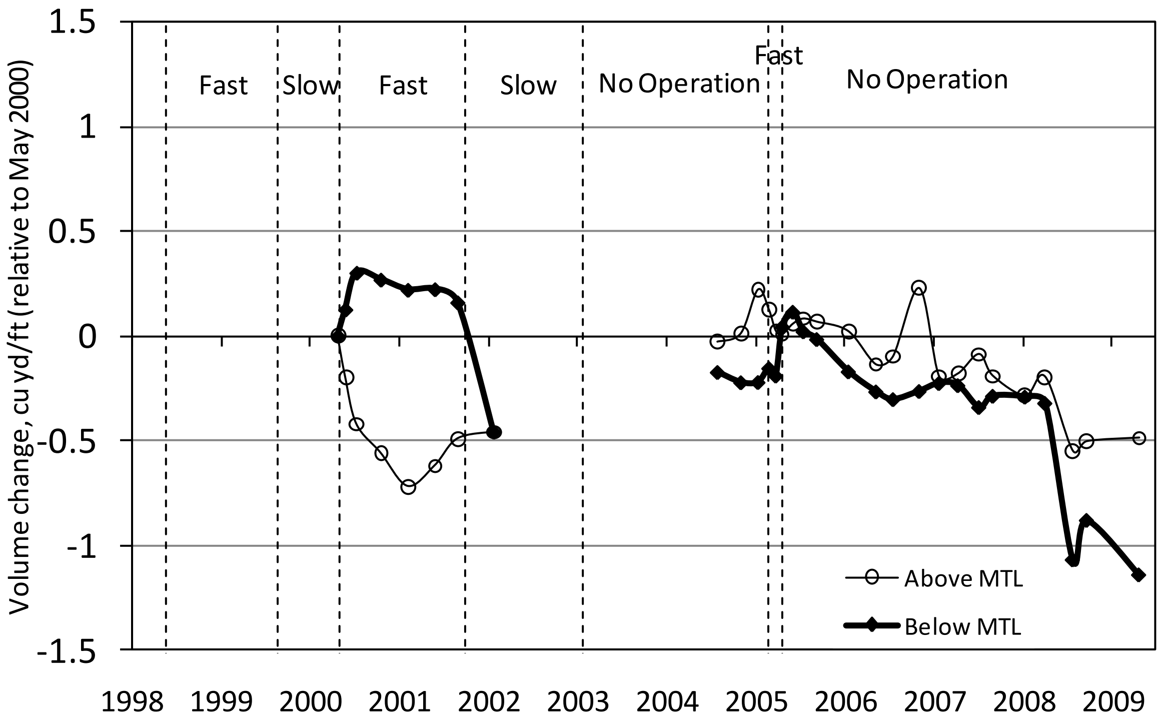

Figure 3. Volume change at PWA over an 8 yr time period relative to May 2000 above and below mean tide level. The intervals of fast, slow, and no operation of passenger only fast ferries are shown with vertical dashed lines. The long term data indicate the beach is gradually losing sediment at this location.

Summary and Conclusions

The gravel tracer measurement from the MSG beach on Point White indicate the system is dominated by alongshore sediment transport from southwest to northeast under existing conditions. The transport is largely driven by wind waves during winter storms. Storms also enhance offshore transport of gravel and cobble and result in flattening of the beach profile and exposure of sand. The combination of car ferry wakes and tidal currents contribute to a weak net alongshore transport to the southwest during non-storm conditions at PWB but not at PWA where the net tidal flux is weaker. Car ferry wakes also contribute to net shoreward transport during non-storm conditions (Curtiss et al., 2009).

Passenger only fast ferry operations may result in a significant cross-shore shift of sediment volume and flattening of the beach profile which can dominate over storm-induced and seasonal variations depending on site specific conditions (Osborne et al., 2007).

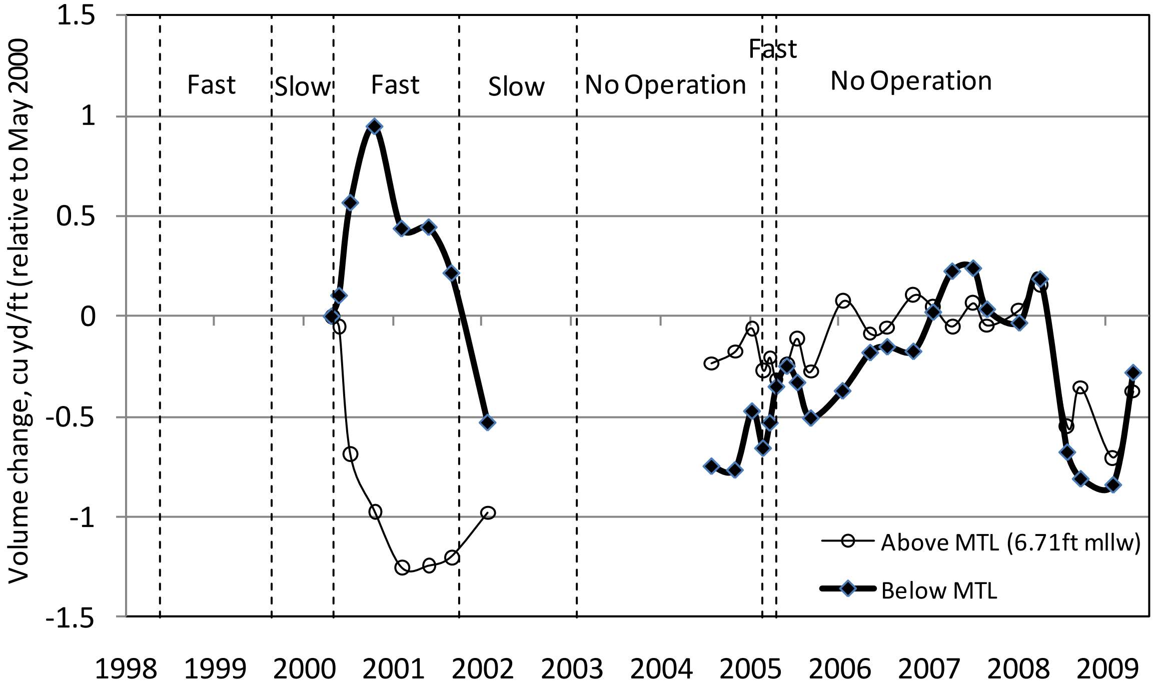

Figure 4. Volume change at PWB over an 8 yr time period relative to May 2000 above and below mean tide level. The intervals of fast, slow, and no operation of passenger only fast ferries are shown with vertical dashed lines. The long term data indicate the beach is not eroding at this location, however the response is complicated by the residual effects of post-fast ferry recovery.

The following observations indicate that the beach is supply limited and undergoing long term passive erosion most likely as a result of construction of bulkheads along the length of the study area:

- The layer of unconsolidated sediment overlying consolidated Vashon till increases in thickness from no more than a single grain of cobble just south of PWA to more than 1 m of MSG at PWB. The median grain size also decreases in the downdrift direction between PWA and PWB consistent with a reduction in supply of finer sediments to the beach and the development of a gravel/cobble lag at the proximal end of the drift cell.
- The differences in the trends in volume change at the two sites are consistent with the above interpretation and may be attributed to their respective location in the alongshore drift cell on

Point White and the relative sediment supply. PWA is near the proximal end of the drift cell where sediment supply is limited whereas PWB is more distal and the sediment supply to the latter is being maintained thus far by erosion of the updrift beach.

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