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The effect of shore armoring on beach slope in mixed sand-and-gravel beaches.

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NONTECHNICAL SUMMARY

Profiles of beaches with bulkheads were compared to natural backshores and the differences in their slopes were correlated. The intention was to look for correlation of slope changes with toe height of seawalls, distance across open water, and beach direction relative to prevailing wind. No significant correlation with any of these single factors was found. However, the combination of higher velocity winds and long exposure across open water may explain some of the changes in profile steepness.

ABSTRACT

This study is a comparison of beach orientation, fetch length, and seawall toe height for 31 pairs of armored/unarmored, mixed sand-and-gravel beaches in southern Puget Sound. Beach profiles from top of berm or toe of armoring to MLW were standardized using NOAA-verified tide tables as a datum for all profiles. Changes in beach profile within each pair were used to evaluate armoring effects. Presumed changes due to armoring were not attributable to a single factor, but there were consistent trends. Fetch length and direction for both prevailing winds and predominant winds were compared. Fetch length, and the angle of the prevailing wind to the beach were compared singly and in groups, but no correlation was found. Comparisons of profiles taken both in spring and in late summer on a small number of beach pairs indicate opposite seasonal trends.

INTRODUCTION

Shore armoring is ubiquitous on Puget Sound's mixed sand-and-gravel beaches, but the sediment dynamics of these beaches are not well understood (Finlayson, 2006). Complicated dynamics result from the combination of fetch-limited wave regime and eroding coastal bluffs. This study seeks clarification on the interaction between shore armoring, fetch length, and beach orientation as expressed in beach morphology. Studying these features on mixed sand-and-gravel beaches may also provide insight into sand or shingle beaches that have a smaller range of sediment sizes.

Puget Sound lies in the northwest corner of the United States and runs roughly

North-South. Prevailing winds are from the south with a small percentage from the north (Fig. 1). This northern component increases during the summer but then returns to the prevailing south and southwest winds.

Puget Sound is a unique fjord-like estuary with some of the same characteristics as a fjord, but with the difference that the glacier moved parallel to, and not towards, the coast. As a result, the glacier's terminal moraine, or sill, is not at the mouth of the fjord, but at the farthest inward portion of the Sound. The study area is located in the main basin and southern reaches of Puget Sound (Fig. 2), near the farthest extent of the last glacial maximum, though this was not a factor in the study. The erosion of coastal bluffs, generally composed of glacial deposits, in Puget Sound supplies sediment to the mixed sand-and-gravel beaches (Shipman, 2009).

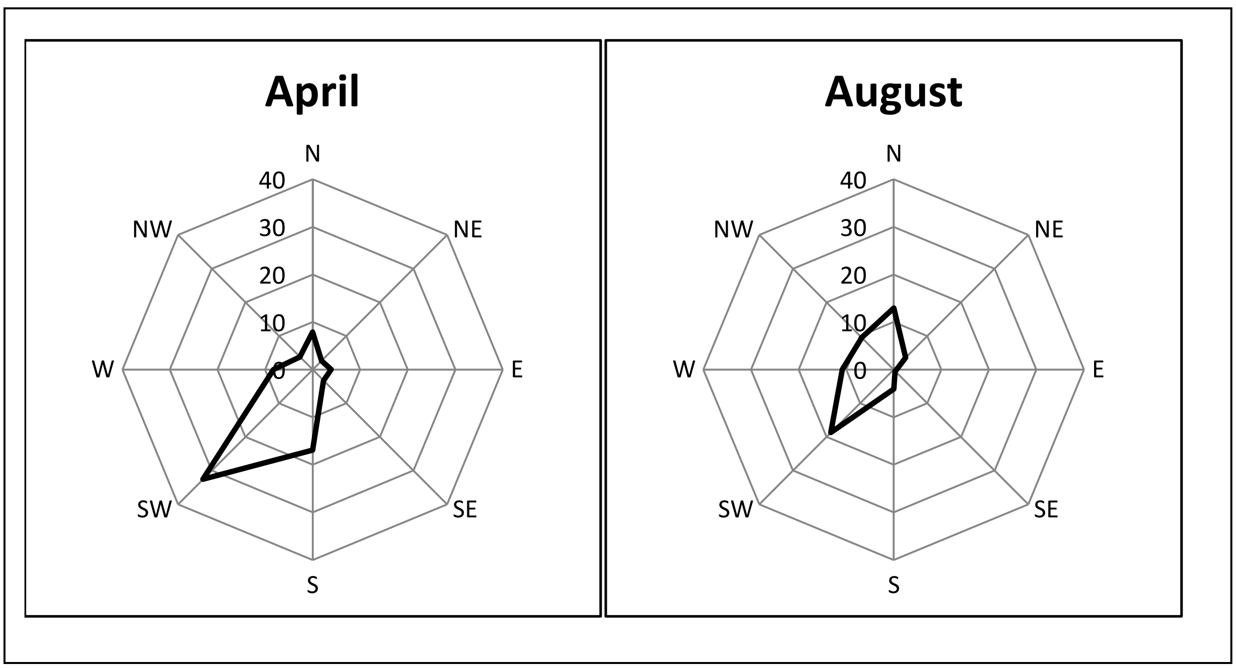

Figure 1 *Wind direction at Seattle-Tacoma International Airport (KSEA) as a percentage of total monthly wind. Percentages are values where the vertices intersect the radial axes. Data from National Climate Data Center (NCDC) for 2011.*

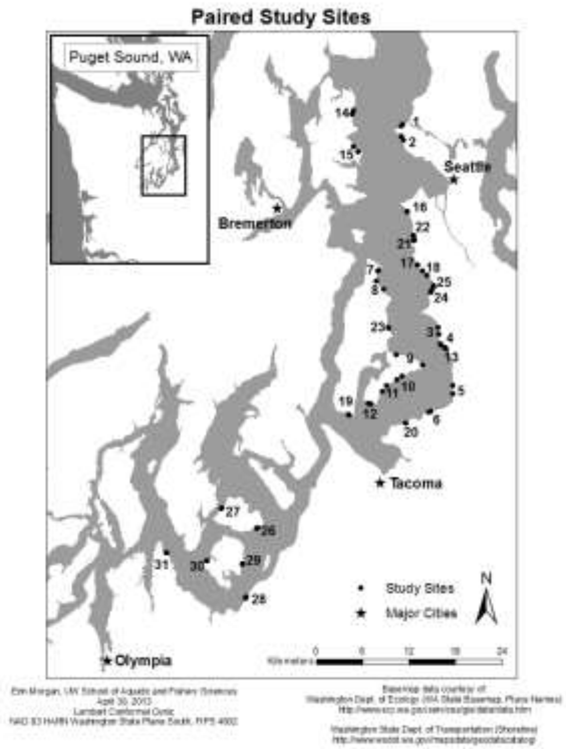

Figure 2 *Study area in central and southern Puget Sound. Study sites are composed of a pair of armored and unarmored beaches*.

It was not within the scope of this project to place wind instrumentation at these beaches so a regional view was taken and the wind direction and velocity as recorded at Seattle-Tacoma International Airport (Sea-Tac) were used for all sites (Fig. 1). Using Sea-Tac as a proxy relies on the assumption that a given regional wind pattern will result in consistent local winds, even though topography might alter the direction locally. This assumption may not always be correct, for example, changes in wind velocity might not interact with local topography in the same way.

Approximately one-third of Puget Sound's 4000 km of shoreline has been armored (Finlayson, 2006; Shipman, 2009). The effect this armoring has on the slope of the mixed sand-and-gravel beaches common to the region has not been established. Puget Sound is isolated from Pacific Ocean swell in its southern region (Finlayson, 2006). This leads to waves that are tightly coupled with local winds and low-energy, fetch-limited wave conditions when compared to the Pacific coast (Finlayson, 2006).

The southern part of the Sound has an irregular coastline oriented SW-NE with variable fetch distances and directions (Schwartz, Wallace, and Jacobsen, 1989). The prevailing wind is from the south and southwest (Fig. 1), but less frequent wind events from directions with longer fetch may have more control on overall beach morphology in Puget Sound (Schwartz et al, 1989).

The tidal range is greater than 4 m in southern Puget Sound and tides occupy the upper half more frequently (Fig. 3, Finlayson, 2006; Shipman, 2009). Locally generated waves are thought to have more influence on the shoreline than tidal currents (Finlayson, 2006).

Once these waves reach a sloped beach-face, they dissipate their energy as the breaking wave churns up sediment. This sediment is transported both perpendicular to the shore and along the shore through cross-shore and longshore transport, respectively.

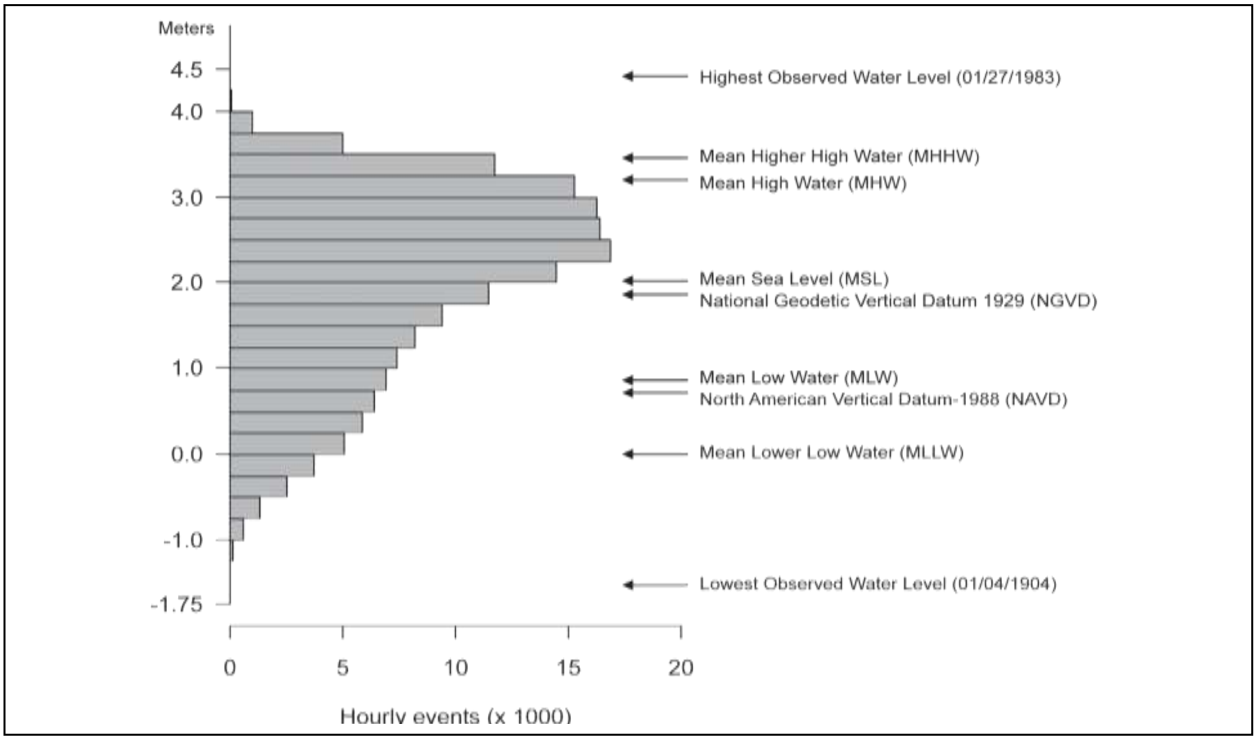

Figure 3 *Hourly tide level histogram and associated tidal datum for Seattle between 1983-2001 (NOS Station: 9447130). Data courtesy of Center for Operational Oceanographic services (CO-OPS) (1901-2005).*

At this point it is unknown what the long-term results of seawall construction on the sediment budget of a beach and the biota that live within or on that sediment will be.

While public awareness has been directed to the conservation needs of the iconic salmon of the Pacific Northwest, less attention has been devoted to the ecological web of animals that they feed upon. Even less attention has been devoted to the sediment that harbors these organisms. While the infauna and epifauna that live in, or on, the sediment are not the basis of this study, it is important to understand the nature of their habitat. Also, with shrinking estuarine habitat due to diking and infill, the need to maximize the food sources available for juvenile salmon is increasingly important.

Sandy beach substrates provide a home for invertebrate prey, but if cross-shore wave activity removes the finer beach sediments, then the remaining cobble, known as a lag layer, instead host kelp, seaweeds, and barnacles (Bilkovic and Roggero, 2008). Although the focus of this study is the sediment regime, and not effects on biota, this information should be useful to those studying the effects of seawall removal on biologic components.

These conditions lead to the questions of whether removing seawalls will increase the biological viability of our beaches and where armoring can be safely added to shorelines that will have minimal impact on the sediment regime or resident biota. Unfortunately, the beaches with the highest need for armoring to prevent erosion may be the ones that would have the largest impact on the sediment regime. The intent of this study is to determine whether fetch length, wind direction, position of armoring, or which combination of these factors, is most highly correlated with the variation in beach slope observed in main basin and southern Puget Sound beaches.

Regardless of the effects on biota, what factor, or combinations of factors, control sediment movement the most? Beach sediment, and finer sediments in particular, are highly mobile and move alongshore, offshore, and onshore through wave and current influences (Patch and Griggs, 2006). Sand is supplied by eroding cliffs, other beaches, and rivers and doesn't remain long in one location (Patch and Griggs, 2006).

METHODS

This study uses both field surveys and data available at Sea-Tac International Airport's weather station (KSEA) and also at NOAA tidal station #9447130. The field surveys were used to determine beach slopes at various locations and the KSEA data were used to establish a wind regime for Puget Sound and to serve as a regional proxy for wind speed and direction. The NOAA tidal station was used to standardize the surveys.

The profiles of thirty-one pairs of beaches were measured as part of a larger survey known as the Beach Blitz. The Beach Blitz grew out of a preliminary study on seawall restoration at Seahurst Park in Burien, WA. Pairs of beaches were chosen that were near each other and were similar in orientation and fetch length. The focus was on finding beaches that only differed in whether they had a natural backshore or a seawall of some type.

Profiles of these beaches were taken using a fiberglass stadia rod, tape measure, and DeWalt™ laser level. The level was positioned at the base of the seawall on armored beaches or at the top of the storm berm on unarmored beaches and measurements were taken through Mean Low Water (MLW) to the lowest point available for a given tide. Measurements were taken every few meters with the interval increased over uniform areas and decreased in order to capture smaller scale changes in sediment or structure of the beach. A visual inspection was made of the surface sediments and notes on sizes or changes in composition were made. Digital photographs were taken at a position along the profile deemed to be representative of the mobile sediments. Mobile sediment was judged to be the area between the most landward extent of barnacles attached to the cobbles and the area near high water that was predominantly sand.

An elevation reading was taken at the waterline and time was noted for each profile. Using NOAA verified tide tables for Seattle, WA a tidal height was calculated for each profile and the profiles were standardized to use MLW as a consistent datum for all beaches. In two cases, where the time and tide had not been noted on one of the pairs, similarity of biota was used to correlate those profiles with their partners.

I used the Seattle station (NOAA Station ID #9447130) to standardize all of the time/tide information for determining MLW. There are other tide stations throughout southern Puget Sound but not all of them have historic, verified data available. I didn't have a verified tidal station near each pair of beaches and I would have had to make an assumption on which station better represented the beaches between two stations. Using one reference point for all of the beaches was more consistent, keeping in mind that the error increases the farther you move from the reference. Due to the convoluted topography of Puget Sound, it was not possible to determine whether Seattle or Tacoma tidal data was the best approximation for each beach without instrumentation at each location. The only direct comparison of beach pairs to each other is the relation of %-contact to total slope in Figure 5. My assumption is that the disparity introduced by this generalization will not have more effect than the discrepancy that would be introduced by the wrong tidal datum.

I used the National Climatic Data Center (NCDC) data collected at KSEA (ID# GHCND: USW00024233) to determine average wind velocity and direction. The station is approximately 3 km from the shore and has an elevation of 112.8 m above sea level. I used the hourly normals for velocity and direction for each month of 2011 and removed any data points that were not taken at 53 minutes past each hour. I also removed any 0 values since they indicate no wind direction or speed. I grouped the wind directions into bins that consisted of 45° arcs centered on the eight major points of the compass. I then took cumulative frequencies of the bins to show the percentage of time the wind blew from each direction. Because I removed all of the data points that registered no wind speed, these percentages are wind directions relative to time the wind was blowing, not relative to the actual hours in a month.

Southwest is the prevailing direction based on these cumulative frequencies. There is a larger component of northerly wind during the third quarter of the year but this component is still less than that of the southwest. During the fourth quarter, southerly wind is larger than southwest but I am making the assumption that this has no effect on beaches measured during the second and third quarters of the year.

Laser and stadia data were converted to profiles relative to MLW. The elevation at waterline was taken and the time was noted. For each beach, using verified tidal heights from NOAA (Station ID #9447130) and the waterline elevation, waterline height relative to MLW was determined. With this height above MLW, the stadia reading at waterline was added and the stadia reading at each measured point was subtracted. This gives a height relative to MLW for all of the points. Using MLW for all of the beach pairs allows general comparisons to be made between them.

The total slopes of profiles were calculated as the slope between the top of the berm or base of the armoring and MLW. Upper slope is the area between the top of the berm or base of the seawall and the major concave-up inflection point where one is evident. The lower slope is between the inflection point and MLW. In some instances there was no readily identifiable inflection point and an arbitrary point was chosen. The absence of an inflection point essentially means that the upper and lower slopes are identical.

Changes in slope are the change in elevation, in meters, over the change in horizontal distance, in meters. Values were determined by subtracting the armored slope from the unarmored slope. Since measured slopes in this study have a 0 elevation at their high point, all slopes are negative. Following this pattern, a positive change-in-slope indicates a steeper armored slope, and a negative change-in-slope indicates a steeper unarmored slope. Relative steepness between one beach pair and another beach pair cannot be compared since this metric is change in beach slope and not a beach slope itself.

RESULTS

The following figures (Fig. 4 and Fig. 5) differentiate between prevailing and predominant wind patterns. Following the definitions of Schwartz et al (1989), prevailing are the winds with the highest frequency and predominant winds are those with the longest potential fetch lengths. Puget Sound winds are strongly bimodal with prevailing winds primarily from the SW, but less frequent winds from the north have a longer fetch when incident upon the beaches in the main basin (Fig. 1).

Under a prevailing regime there is a cluster of pairs with not much difference in slope for fetches up to 11 km (Fig. 4). Both beach pairs with fetches longer than 11 km have a steeper unarmored section. Of the four beach pairs with slope differences greater than 0.04, three have steeper armored sections with fetches between 1-9 km. The last pair of the four has a steeper unarmored section and a fetch of almost 16 km. All of the pairs that experience an offshore prevailing wind are clustered on the y-axis between the values of 0.04 and -0.02, with the exception of one beach pair with a much steeper unarmored section that has a value near -0.07.

The predominant fetch graph shows a cluster of beach pairs between 5-20 km that have slope differences between -0.03 and 0.08 (Fig. 5). There is a second smaller cluster between 35-50 km. The armored pairs with a difference greater than 0.04 all occur between 10-20 km. The unarmored sections that have differences greater than -0.04 occur at longer fetch lengths, between 25-45 km.

Total slope uses an approximation from Finlayson's (2006) histogram of tidal distribution in Puget Sound. Elevation of the seawall toe is standardized to MLW (Fig. 3). The period of time that tidal sea level is above the base of the armoring is represented as a percentage and compared to changes in slope between armored and unarmored sections of each pair (Fig. 6). This distribution appears nearly symmetrical about the x-axis. There is not an obvious trend that favors either steepness condition with increased contact, though increased contact appears to increase the difference in slope within each pair. There is a cluster of pairs above 50%-contact for both steeper armored and unarmored beaches that exhibit greater differences in slope. The point showing no contact is treated as anomalous, since tidal height rarely impacts this seawall.

When dividing the pairs into spring profiles and autumn profiles, all of the pairs with a negative sine angle are offshore wind patterns and therefore not comparable to onshore wind conditions (Fig. 7). Two trends are noticeable when looking at the positive side of the x-axis. April slope differences favor steeper armored beaches when wind is almost parallel to the beach and unarmored beaches are steeper when wind is perpendicular. The opposite appears to happen for August winds with increased armored slope as winds become more perpendicular to the beach.

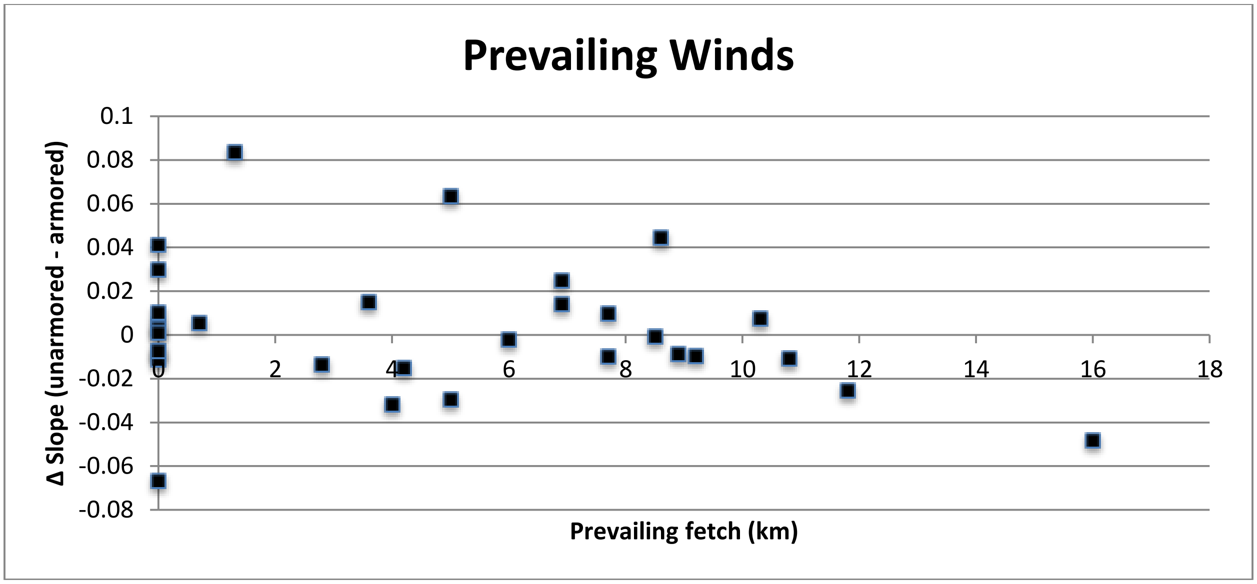

Figure 4 *Prevailing wind regime, in kilometers of fetch, compared to change in slope between armored and unarmored sections of 31 pairs of beaches. Each data point represents a pair of beaches. Grouped data points on the y-axis are beaches within the study that have prevailing offshore wind conditions. Positive change in slope indicates a steeper armored beach and negative change in slope indicates a steeper unarmored beach in each pair.*

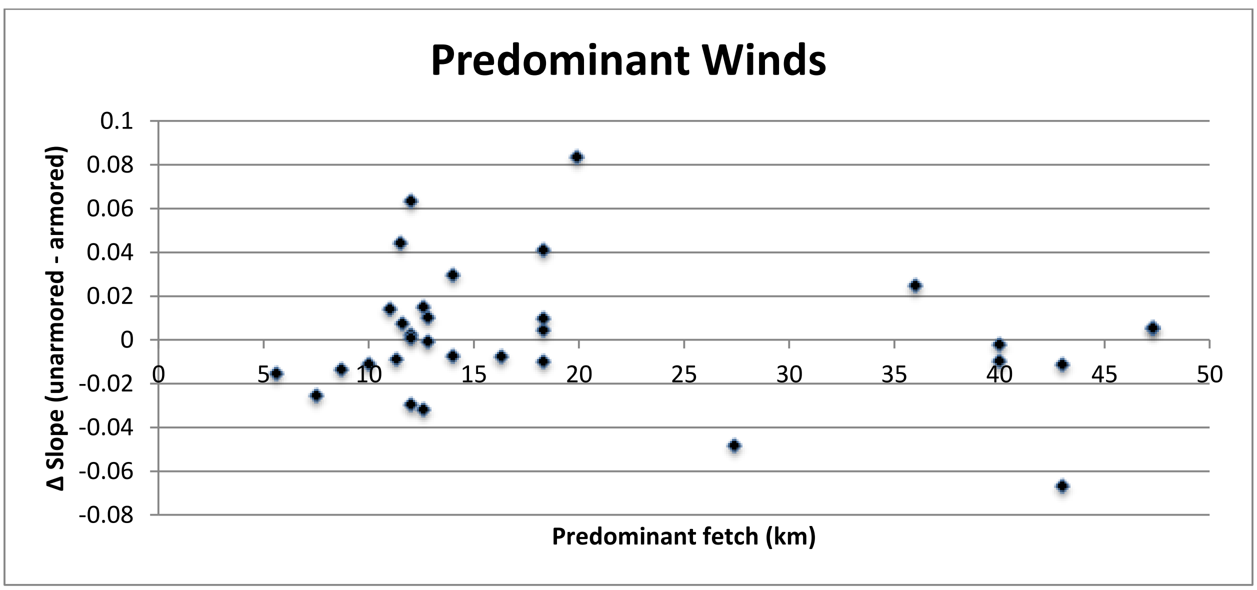

Figure 5 *Predominant wind regime, in kilometers of fetch, compared to change in slope between armored and unarmored sections of 31 pairs of beaches. Predominant fetch is the direction of the longest possible onshore fetch for each pair of beaches. The change in slope is positive for steeper armored beaches, and negative for steeper unarmored beaches within each pair.*

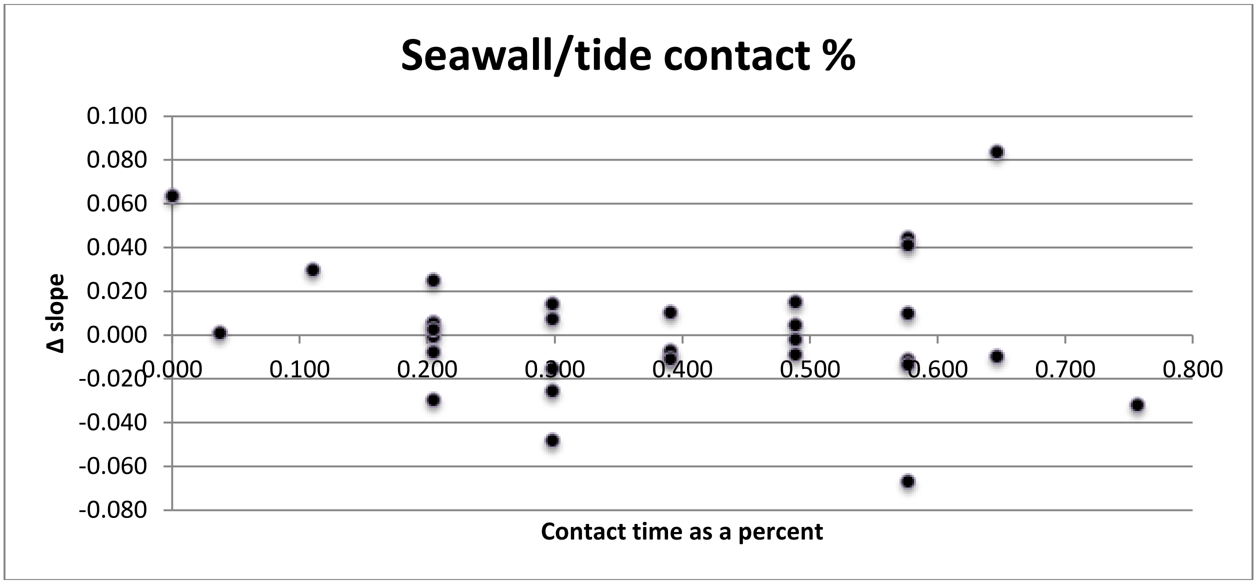

Figure 6 *Changes in slope relative to the percent time the tide is in contact with a seawall. A lower contact percentage indicates a seawall higher on the beach face.*

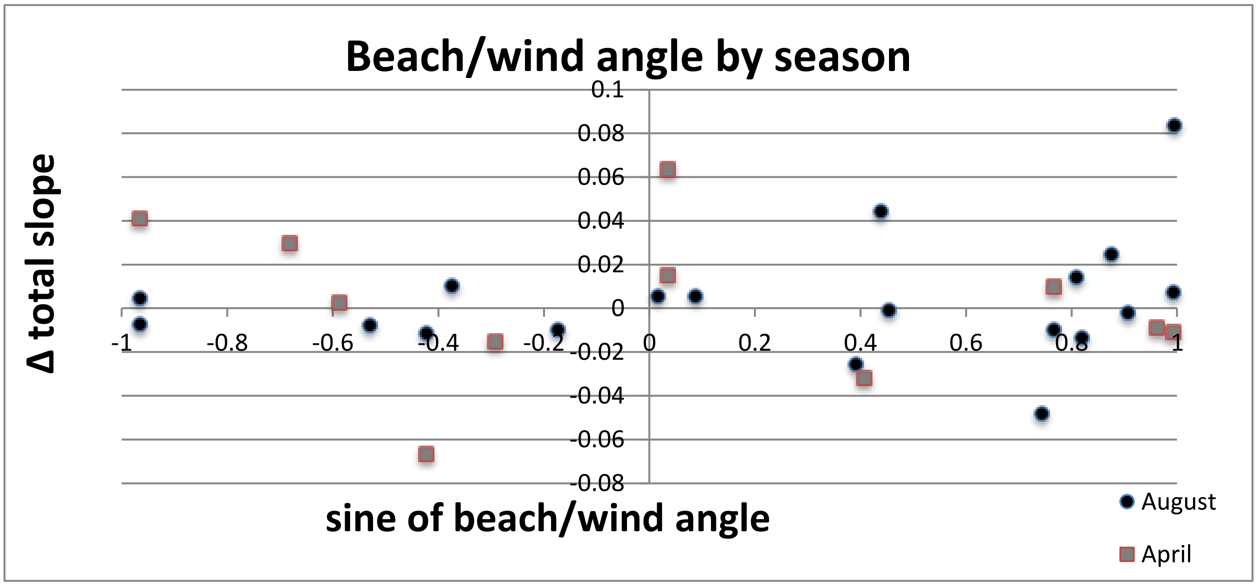

Figure 7 *Study beaches divided into April and August groups by the date profile was taken. Negative sine values indicate offshore wind conditions, positive sine values indicate onshore wind conditions. Positive total slope values indicate steeper armored beaches and negative values are steeper unarmored beaches. Sine values of 1 indicate orthogonal winds and of 0 indicate parallel winds to beach.*

DISCUSSION

Beach Pair Differences

When surveying these beaches it seems apparent that the armored beach is steeper. This is subjective and apparently erroneous. It is important to remember that beach steepness only applies within each pair. The way I processed my data does not allow comparisons of steepness between beaches. Rather than looking at the steepness of the total beach face or the upper and lower units that I have defined, perhaps we should be looking at where sediment is being transported.

It is evident in the beach profiles collected for this study that the MLW datum is nearer to the seawall than to the top of the unarmored berm. It is also evident that there is great variation in beach morphology (Fig. 8). This distance varies from a few meters to 40 meters in the profiles taken for this study. For the most part, this is due to the seawall being built seaward of the berm and whether its placement initiates change in the lateral position of the MLW datum is not yet known.

There is great variation between beach pairs as well as within armored/unarmored profiles (Fig. 8). The two beaches in Figure 8 are located 5 km apart across an open stretch of water; McNeil Island (#26) faces SE while Anderson Island (#29) faces east. None of the fetches in this part of Puget Sound are much beyond 10 km, nothing like the long fetches available in the main basin farther north. The armoring put in place at McNeil Island is the closest to MLW of all the beach pairs studied.

Two interesting thing about these pairs is that the slope of McNeil Island (#26) armored is the same as the pair at Anderson Island (#29), and, that Anderson Island slopes are virtually indistinguishable from each other. The similarity of armored and unarmored on Anderson Island could be a coincidence or it could be the result of armoring. McNeil and Anderson Islands have almost the same exposure and fetch; were McNeil Island beaches more similar before the addition of the seawall? Either the McNeil Island pair had a shallower slope before the armoring steepened it and the similarity to Anderson Island is a coincidence, or both pairs had the same slope and sediment that used to be deposited on the upper part of McNeil armored is now deposited on McNeil unarmored resulting in a shallower unarmored beach at McNeil Island.

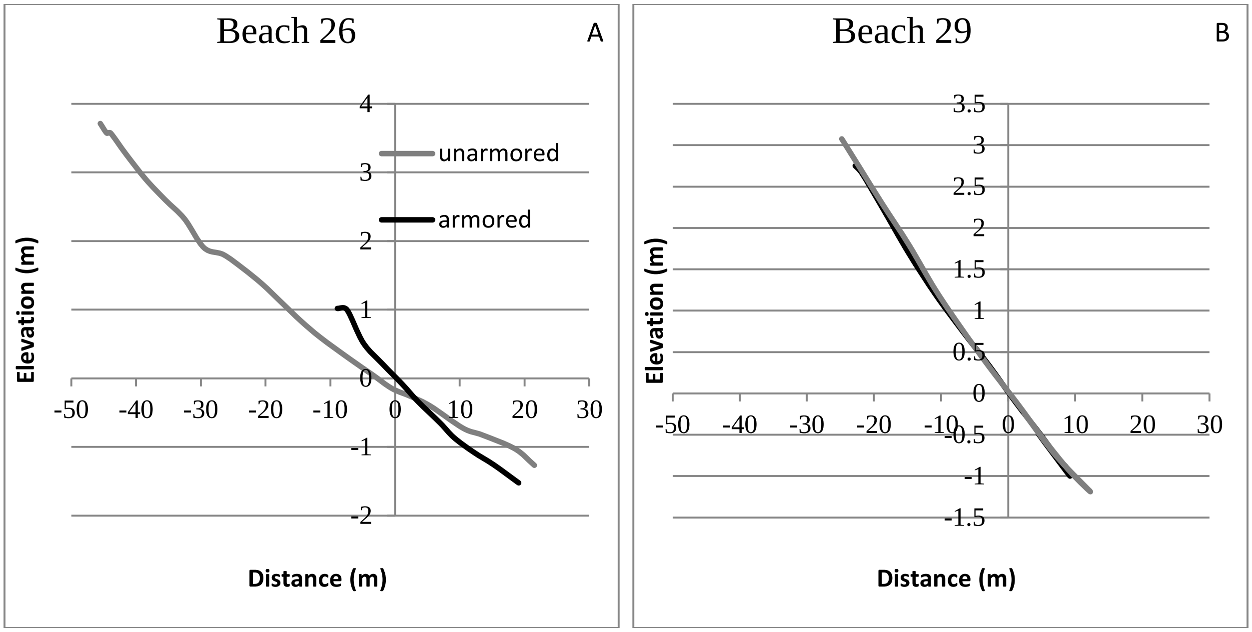

Figure 8 *Profiles of Beaches #29 (Anderson Island) and #26 (McNeil Island) showing elevation and horizontal distances between MLW and top of berm or toe of seawall.*

I was not able to separate the presumed changes that occurred to the beach in front of a seawall from the effects that the armoring would have on downdrift unarmored beaches. Since I am unable to separate these effects, I cannot assume that an unarmored beach is unaffected by armoring. I should have either bracketed an armored beach by taking profiles of unarmored sections on both sides, or vice versa, whichever was appropriate to each case. In retrospect, making sure that the unarmored beach is updrift of the armored beach, should separate the downdrift, longshore effects from the cross-shore effects of armoring.

Wave Activity

The assumption is that wave energy impacting the seawall will drive sediment seaward. Most of the sediment on Puget Sound beaches is from the erosion of glacial deposits in the form of coastal bluffs (Shipman, 2010). Seawalls also reduce the sediment that is supplied to the drift cell in each area (Schwartz et al, 1989).

Armoring of beaches causes the cross-shore, instead of longshore, transport of existing sediment and can result in a reduction of the sediment budget (Miles, Russell, and Huntley, 2001; Lucrezi, Schlacher, and Robinson, 2010). On the California coast it was found that “coastal armoring, which prevents seacliff and bluff sediments from reaching the beach, could have a significant impact on the sediment budget” (Runyan and Griggs, 2003).

Sediment is driven off the upper beach face through wave energy impact on the seawall, with the greatest effect occurring under large wave and shallow water conditions (Miles et al, 2001). Where would this sediment go? Either alongshore, adding sediment to the upper beach face downdrift, or cross-shore, adding sediment to the low-tide terrace seaward of the armoring. Both of these instances would lead to a shallower armored beach face when compared to its unarmored partner.

In Figure 4, there are steeper armored slopes with shorter fetches. Shorter fetches should lead to shorter wave periods since waves have less time to develop. In the same figure, distances longer than 10 km lead to steeper unarmored sections. A steeper unarmored section is the same condition as a shallower armored section. If the longer fetches do lead to longer wave periods and a deeper wave base, any activated sediment could be deposited offshore rather than transported by longshore drift.

Figure 7 indicates steeper armored beaches in April with winds parallel to the shore and shallower armored beaches when winds are perpendicular. Stronger orthogonal winds in April would build waves with longer periods and would drive sediment offshore and result in shallower armored slopes. The same figure shows the opposite pattern in August. August winds are milder than April winds resulting in shorter wave periods and shallower wave base. In this case, waves orthogonal to the beach are depositing sediment high on the beach face through swash and backwash.

This indicates that a critical threshold between transport processes controls sediment delivery. A certain critical stress and turbulence need to be maintained in order to activate sediment and keep it entrained in the water column. Lower seabed stress due to lighter winds or shorter fetches would lead to onshore or longshore transport. Higher bed stress due to higher winds or longer fetches would lead to sediment suspended in the water column and cross-shore transport. It is possible that it requires both long fetches and high wind speed to generate the necessary bed stress and reflected wave energy to move that sediment cross-shore.

If this is true, then the combination of fetch length and wind speed are the primary controls on beach steepness with respect to seawalls. High velocity over a short fetch, or low wind velocity over a long fetch wouldn’t generate the necessary bed stress to activate sediment and keep it suspended.

CONCLUSIONS

Changes in beach profile, as shown by relative steepness within beach pairs, may be attributable to shore armoring. Beach orientation to prevailing wind, fetch length, toe height of seawall, and seasonal changes in wind velocity all appear to influence the sediment dynamics on beaches in southern Puget Sound and its main basin. Also, the interaction of these factors may change, with a given factor having more bearing on sediment movement during a particular season, and then relinquishing primacy during other seasons.

Location of armored beach section downdrift from its unarmored partner is more important than previously thought. I was not able to differentiate between changes on the beach fronting the seawall from changes that may have happened to the unarmored beach as a result of altered beach dynamics. There are three areas that would help clarify this:

- How much sediment passes through an area in front of a particular seawall, and what percentage is longshore compared to cross-shore transport?
- What percentage of a drift cell has to be armored in order to change the sediment transport regime in that cell?
- Is it possible to separate the overall transport from seasonal fluctuations?

ACKNOWLEDGEMENTS

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