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WAVE ENERGY DISSIPATION BY INTERTIDAL SAND WAVES ON A MIXED-SEDIMENT BEACH

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Abstract: Within the surf zone, the energy expended by wave breaking is strongly influenced by nearshore bathymetry, which is often linked to the character and abundance of local sediments. Based upon a continuous, two year record of Argus Beach Monitoring System (ABMS) data on the north shore of Kachemak Bay in southcentral Alaska, we model the enhancement of wave energy dissipation by the presence of intertidal sand waves. Comparison of model results from simulations in the presence and absence of sand waves illustrates that these ephemeral morphological features can offer significant protection to the backing beach and sea cliff through two mechanisms: (1) by moving the locus of wave breaking seaward and (2) by increasing energy expenditure associated with the turbulence of wave breaking.

INTRODUCTION AND BACKGROUND

Nearshore sand along the northern coast of Kachemak Bay, Alaska, is transported as discrete intertidal sand waves that migrate over a coarse cobble substrate (Figure 1). The rate of sand wave migration is strongly seasonal and responds directly to the local environmental conditions (Adams et al., 2004). We hypothesize that the presence of these intertidal sand waves substantially decreases the amount of wave energy delivered to the sea cliffs and the upper beachface. This paper briefly describes the regional geomorphic and oceanographic setting, reviews the results of a sand wave migration study, and applies a wave energy dissipation model to test this hypothesis.

Figure 1. Intertidal sand waves exposed at low tide along the north shore of Kachemak Bay, Alaska.

Geomorphic and Oceanographic Setting

Kachemak Bay and its surrounding landscape on the western Kenai Peninsula in south central Alaska is a dynamic geomorphic setting exhibiting the effects of active tectonics (uplift, subsidence, volcanism, and frequent earthquakes), recent glaciation (u-shaped valleys and abundant glacial till), fluvial action (incised coastal streams), and coastal processes (wave-induced sea cliff retreat and littoral sediment transport). Waves approaching the north shore of Kachemak Bay are produced locally within Lower Cook Inlet by winds that blow through gaps in the topography on the western shore. The greatest fetch is on the order of 100 km (from a direction of ~250^{o}) resulting in wave heights of approximately 3-4 meters with wave periods rarely exceeding 6 seconds. Strong seasonal variations in wave height reflect the contrast between quiescent summer meteorological conditions and the stormy winter conditions. Megatidal conditions (8+m spring tidal range) coupled with the gentle slope of the intertidal zone on the north shore (~0.015) of Kachemak Bay expose a nearly 500 m wide beach at low tide in front of the city of Homer. Intertidal beach sediments along the north shore of Kachemak Bay are strongly bimodal. The coarse component is glacial till, consisting of cobbles and boulders, comprising the rocky substrate. The fine component is medium-to-coarse, well-sorted sand normally distributed with a mean of approximately 0.25 mm, and organized into discrete intertidal sand waves, whose wavelengths range from ~20 m to ~200 m, and have a maximum thickness at their leading edge crest of 1-2 m.

Argus Monitoring Methods

We use an Argus Beach Monitoring System (ABMS) to examine the structure and migration rates of these intertidal sand waves (Lippmann and Holman, 1991). This system employs eight digital cameras in which the overlapping geo-referenced digital photos are merged and ortho-rectified, to yield hourly map views of the study region. To obtain a quantitative assessment of the effect of the intertidal sand waves on coastal wave energy delivered to sea cliffs, we employ the wave energy dissipation model proposed by Thornton and Guza (1983).

Sand Wave Migration Rates

Sand waves travel eastward, at an annually-averaged rate of 275 m/yr (~0.75 m/d). Strong seasonality in migration rates is evidenced by the contrast of rapid early winter transport (2.23 m/d during mid Nov. to early Jan.), with slow summer and fall transport (0.13 m/d during May through Oct.). The majority of sediment transport occurs during large wave events. The greatest weekly-averaged rates of sand wave migration, exceeding 4 m/d during the winter of 2003, coincided with wave heights exceeding 2 m. (Adams et al., 2004) Because Kachemak Bay is partially enclosed, the waves responsible for these maximum nearshore sediment transport rates are locally generated by strong winds blowing from the southwest and west, the direction of greatest fetch.

MODELING WAVE ENERGY DISSIPATION

We turn toward a quantitative assessment of the effect of intertidal sand waves on coastal wave energy delivered to sea cliffs. A wave energy dissipation model is used to determine the amount by which wave energy is reduced by the presence sand waves. We expect the sand waves to act as a natural buffer to the sea cliffs: (1) by moving the position of wave breaking seaward, and (2) by enhancing the amount of turbulent energy dissipation once wave breaking is initiated.

The majority of wave energy expenditure occurs within the surf zone, dominantly through the process of wave breaking and to a much lesser extent through frictional loss as wave orbitals drag over the shallow sea bed (Komar, 1998). The beach morphology strongly influences the spatial pattern of wave energy dissipation. Steep beaches that promote plunging breakers confine the dissipation to a narrow region near the critical depth of wave breaking, whereas on gently-sloping beaches that generate spilling breakers dissipation occurs over a wide region (Komar, 1998). Several existing models that predict decay of wave heights and wave energy dissipation due to frictional drag and wave breaking within shallow water have been successfully tested against field data (e.g., Thornton and Guza, 1983; Dally et al., 1985; Baldock et al., 1998; Battjes and Janssen, 1978). The common starting point in the development of these models is the wave energy flux balance

$$\frac{\partial\left(EC_g\right)}{\partial x} = -\varepsilon_f - \varepsilon_b \qquad (1)$$

where E is wave energy density. C_g is wave group speed defined by

$$C_g = \frac{C}{2}\left[1 + \frac{2kh}{\sinh(2kh)}\right] \tag{2}$$

ε_f is the loss of wave energy flux due to friction and ε_b is the loss of wave energy flux due to wave breaking, k is the wave number, defined as $2\pi/L$ (L is the wavelength), and h is the local water depth. The majority of the energy is lost in wave breaking and the turbulence associated with the propagation of broken surf bores.

We employ the model proposed by Thornton and Guza (1983), in which the dissipation functions, for friction and wave breaking, respectively, are defined as

$$\varepsilon_f = \rho c_f \frac{1}{16\sqrt{\pi}}\left[\frac{2\pi \bar{f} H_{rms}}{\sinh kh}\right]^3 \tag{3}$$

and

$$\varepsilon_b = \frac{3\sqrt{\pi}}{16}\rho g B^3 \bar{f}\frac{H_{rms}^5}{\gamma^2 h^3}\left[1 - \frac{1}{\left(1 + \left(H_{rms}/\gamma h\right)^2\right)^{5/2}}\right] \tag{4}$$

where c_f is a bed friction coefficient, $\bar{f}$ is average frequency of incident wave field, H_{rms} is the root-mean-square wave height within the surf zone, B is a breaker coefficient (usually set to 1), and γ is the depth – limited wave breaking coefficient.

The analysis of the Argus images documents changes in the intertidal bathymetry, due principally to the presence or absence of sand waves at a particular location. Our goal within these numerical experiments is to investigate how changes in nearshore bathymetry influence changes in the spatial pattern of wave energy dissipation within the nearshore zone. This ultimately could affect the amount of geomorphically effective wave energy reaching the sea cliff during periods of high tide.

Four principal inputs are prescribed in the model – two wave parameters, tide level, and bathymetry while the principal outputs are the wave energy dissipation values (ε_f and ε_b) everywhere along the bathymetric profile. The wave field is defined by H_{rms} outside the surf zone and a chosen wave period. The model tracks the H_{rms} which is the only parameter necessary for Rayleigh distributed waves. Therefore the model deals with an entire distribution of random wave heights in a probabilistic manner, albeit for steady state conditions. The wave height evolves during shoaling according to linear wave theory, and the wave energy dissipation relations (Equations 1 through 4). Moving stepwise shoreward, these dissipation values decrease the wave energy flux through the surf zone, from which wave energy density and wave height can be recalculated.

Typical outputs for two chosen tidal levels are shown in Figure 2 (mid-tide) and Figure 3 (high tide). The sand wave is present in the June profile and absent at this transect in the December profile (Figure 2A and Figure 3A). Nearshore wave heights decrease over the sand wave more abruptly at mid-tide than at high tide (Figure 2B and Figure 3B).

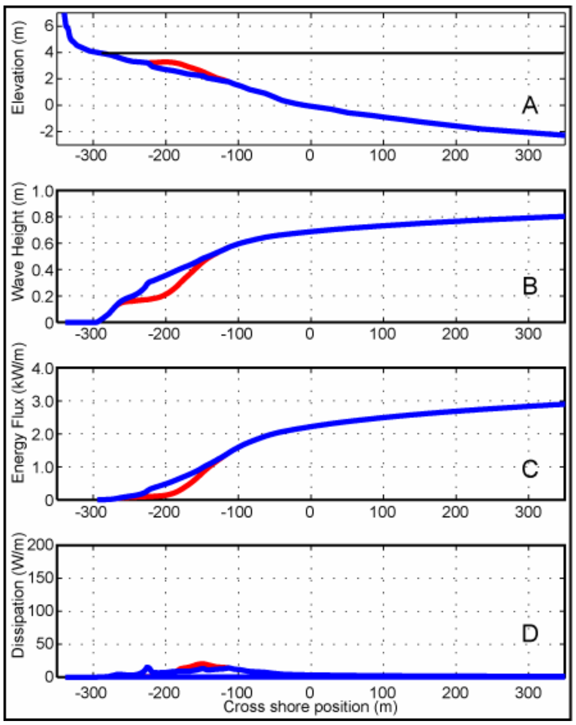

Figure 2. Output from wave dissipation modeling for mid-tide. Red and blue lines represent June 2003 and Dec. 2003 bathymetry and model outputs, respectively.

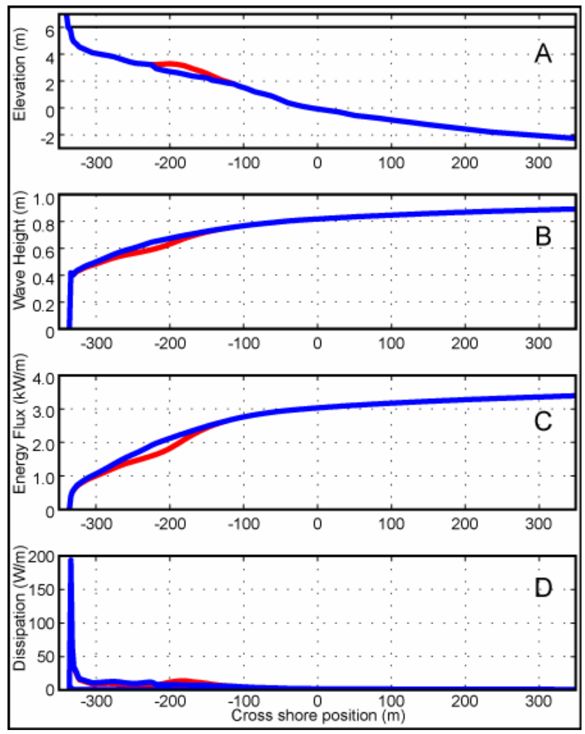

Figure 3. Output from wave dissipation modeling for high-tide. Red and blue lines represent June 2003 and Dec. 2003 bathymetry and model outputs, respectively.

Correspondingly, wave energy flux is more pronounced over the sand wave at mid-tide than at high tide (Figure 2C and Figure 3C). During high tide, significant wave power (~200 W/m) is delivered to the base of the seacliff (Figure 3D), while in contrast the land-sea interface at mid-tide is approximately 50 m seaward of the sea cliff base. At mid-tide the wave energy is dissipated by wave breaking and friction on the beach completely.

Spatial patterns of wave energy dissipation due to wave breaking (ε_b) and friction (ε_f) over the June and December profiles, for the simulated conditions reported in Figure 2, are given in Figure 4. Maximum dissipation due to wave breaking (Figure 4A) is roughly 50 times greater than maximum dissipation due to friction (Figure 4B). Dissipation by wave breaking appears to correspond to steepness of bathymetric profile.

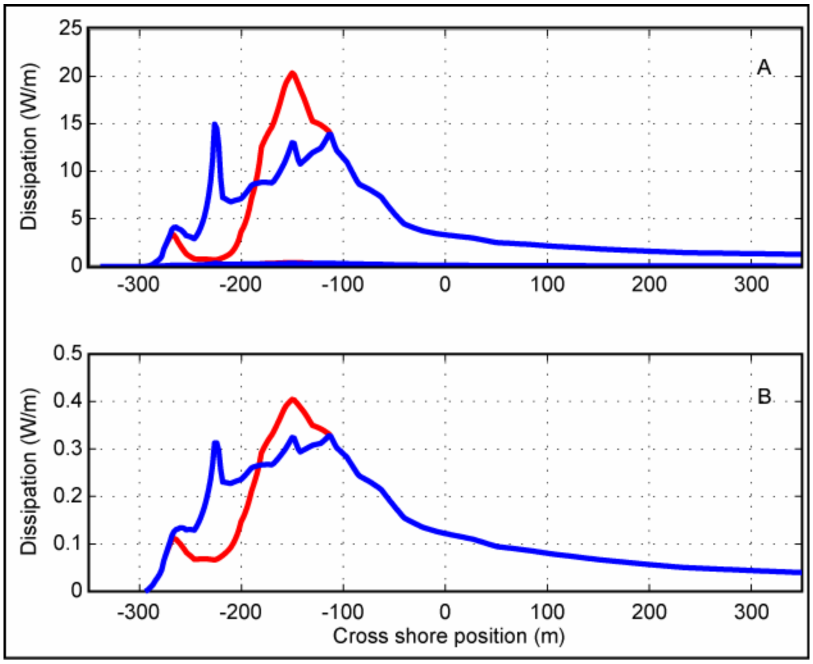

Figure 4. Modeled wave energy dissipation functions across June 2003 (red) and December 2003 (blue) bathymetric profiles for a chosen suite of oceanographic conditions. (A) Spatial pattern of wave energy dissipation due to wave breaking (ε_b). (B) Spatial pattern of wave energy dissipation due to friction(ε_f). Units of dissipation are watts per meter of wave crest length.

The following discussion of wave energy dissipation modeling results is aided by the definition sketch provided in Figure 5. It shows the sand-free, cobbly December beach profile, and the June beach profile, essentially the same, except for the presence of the intertidal sand wave, that shows up as a bulge from -110 m to -225 m in the cross shore, and between 1.75 m and 3.25 m in elevation.

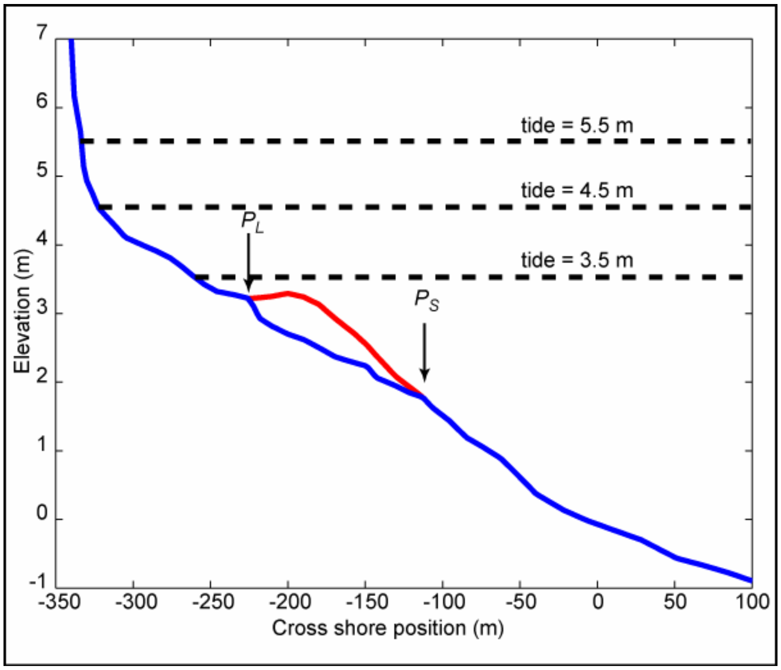

Figure 5. Definition sketch for wave energy dissipation modeling. December (blue) and June (red) beach profiles are identical except for the presence of a sand wave. Three tidal levels are shown as dashed black lines. Positions of simulated wave conditions (wave height and energy flux) are shown on either side of the sand wave and labeled accordingly (P_L - landward position, P_S - shoreward position).

We define the locus of wave breaking as the cross shore location at which the maximum rate of wave energy expenditure due to wave breaking occurs; where ε_b is at a maximum. Figure 6 shows the breaking wave energy dissipation function for three separate tidal levels over both the June and December beach profiles (six simulations in all). The energy dissipation curves (lower panel of each pair) show the seaward change in position of the locus of wave breaking due to the presence of the sand wave. The change in position is consistently approximately 70-75 m.

As a final target for the modeling, we evaluate explicitly the effect of the sand wave on wave energy dissipation; which can also be thought of as energy removal. We do this by comparing the energy fluxes at two positions on the beach profile; one immediately seaward of the lower extent sand wave (location P_S, Figure 5) and one immediately landward of the upper extent of the sand wave (location P_L, Figure 5). The quantity of wave energy flux at P_S is the same as that for the June (sand wave present) and December (sand wave absent) beach profiles, for a prescribed set of offshore conditions. The amount of wave energy remaining at P_L is considered to be a proxy for the effective energy available to drive sea cliff retreat and is different for the June and December profiles.

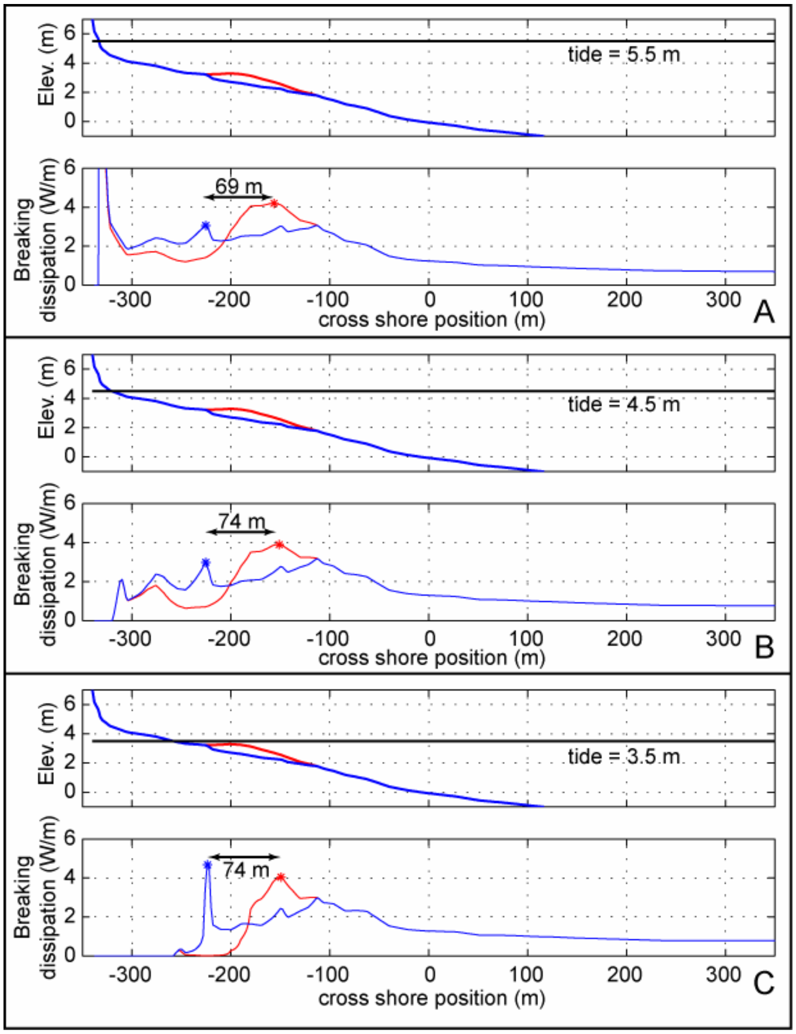

Figure 6. Effect of sand wave presence on changing the locus of wave breaking. (A) profiles and ε_b functions at 5.5 m tide. (B) profiles and ε_b functions at 4.5 m tide. (C) profiles and ε_b functions at 3.5 m tide. Locus of wave breaking is shown on each ε_b function with an asterisk.

Figure 7 shows the results of 34 simulations of cross shore wave energy dissipation over both the June and December profiles at varying tide levels (2 m to 6 m above mean lower low water) for typical wave conditions in Kachemak Bay (Ho = 1 m, T = 2 s). Figure 7A and Figure 7B show that wave height and wave energy flux, respectively, decrease shoreward and respond to the presence of the intertidal sand wave. Figure 7C and Figure 7D display the percent wave height decrease and percent wave energy flux loss between stations P_S and P_L , respectively. In the presence of the sand wave, wave heights and energy fluxes are lowered to greater proportions than in the absence of the sand wave, irrespective of tide. The amount by which wave dissipation is enhanced (taken as the difference between the red and blue curves on Figure 7C and Figure 7D) is plotted in Figure 7E and Figure 7F. Maximum dissipation enhancements are 19% and 15% for wave height and wave energy flux, respectively, and occur at mid-tide for typical Kachemak Bay conditions (*Ho* = 1 m, *T* = 2 s). The same analysis of model output is shown on Figure 8, but for extreme conditions within the bay (*Ho* = 2 m, *T* = 8 s); conditions suspected responsible for driving the majority of sea cliff retreat in the area. Wave heights and energy fluxes are much greater, and percent losses higher than for typical bay conditions. The tide level at which dissipation enhancement (as measured by differences in wave energy flux losses between the June and December profiles) is much higher (tide = 5.25 m) at the extreme conditions (Figure 8F).

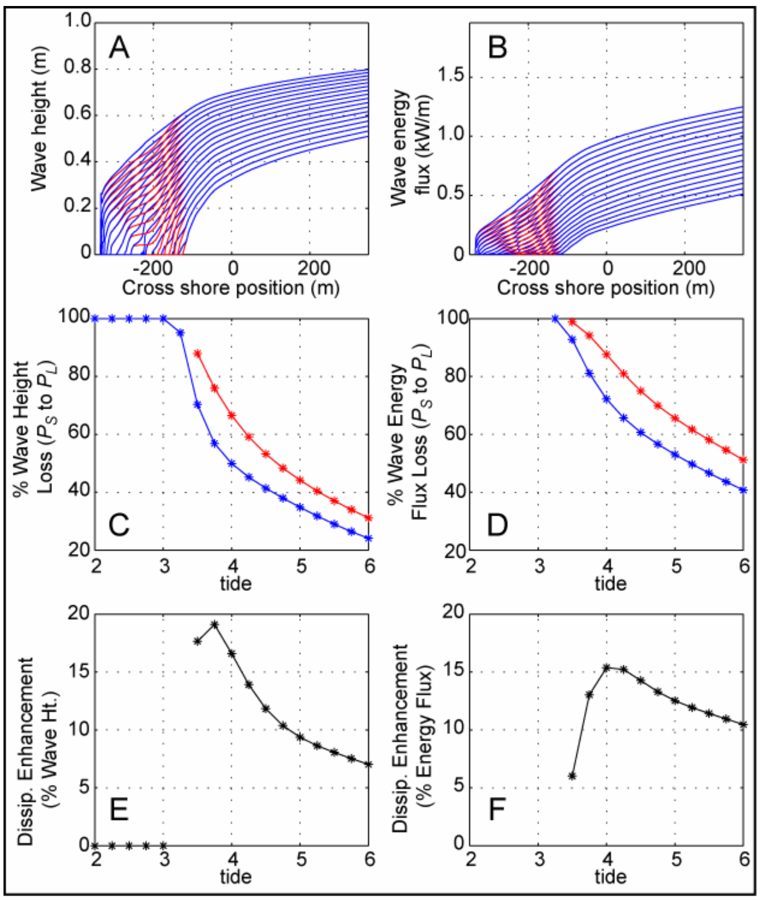

Figure 7. Wave energy dissipation modeling results for typical Kachemak Bay wave conditions (Ho=1 m, T=2 s). (A) Wave heights through the surf zone for all 34 simulations. Red lines computed for June profile (sand wave present). Blue lines computed for December profile (sandwave absent). (B) Simulated wave energy fluxes. (C) Percentage wave height loss between P_S and P_L. (D) Percentage wave energy flux losses. (E) Dissipation enhancement for sand wave presence derived from wave height output (difference of red and blue curves in C.) (F) Dissipation enhancement for sand wave presence derived from wave energy flux output (difference of red and blue curves in D.)

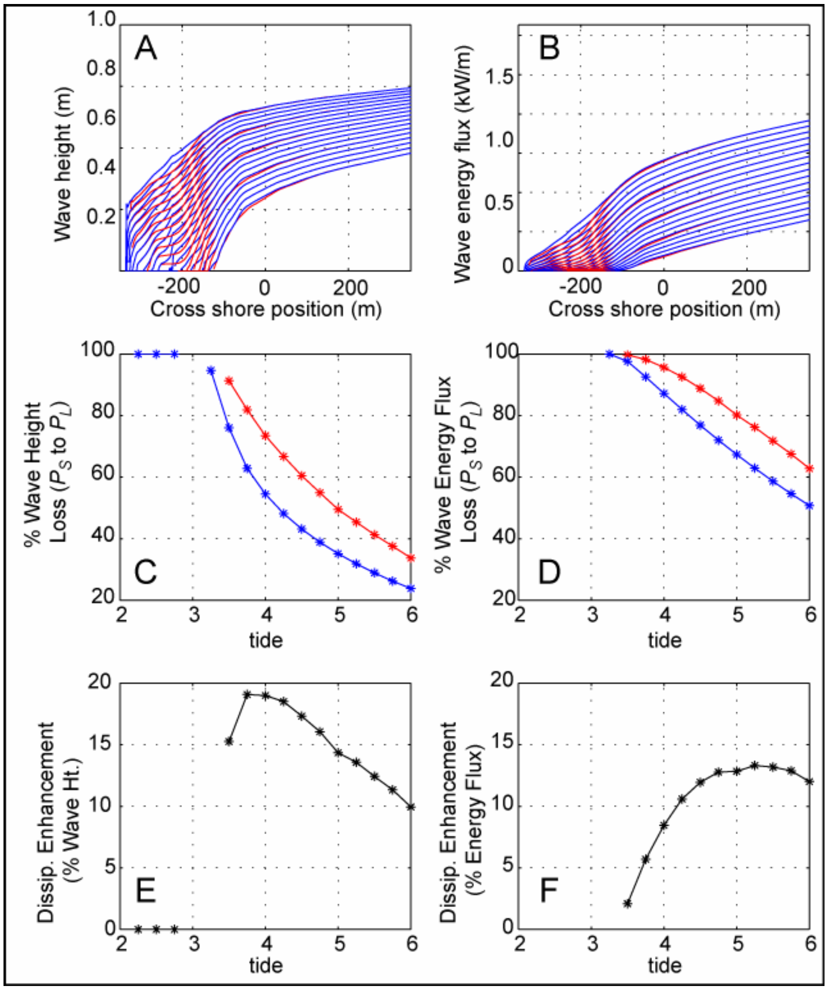

Figure 8. Wave energy dissipation modeling results for extreme Kachemak Bay wave conditions (Ho = 2 m, T = 8 s). See caption of Figure 7 for individual panel explanations (A-F).

DISCUSSION AND CONCLUSIONS

In this study, we examine the effects and influences of large wave-like bedforms of nearshore sediment on wave energy dissipation. This is an important variable in two significant processes. Dissipation on the beach reduces the amount of wave energy available for sea cliff retreat – a topic of significant geomorphic interest, and a concern for coastal property management. Wave energy dissipation is also strongly linked to the development of longshore currents, which are responsible for the evolution of beach morphology by moving littoral sediment.

As viewed from the perspective of the sand wave, there is a positive feedback operating within this system; the existence of a sand body enhances wave energy dissipation over the sand body, which in turn increases the amount of turbulent energy used to entrain and mobilize the sediments, propagating the sand body along shore, provided that there is an oblique component to the incident wave field. As viewed from the perspective of the sea cliff, there is a potentially valuable negative feedback; large waves attack the sea cliff, driving retreat, however the eroded material now in front of the sea cliff lowers the assailing energy of future incoming waves, protecting the cliff from further retreat.

We model wave energy dissipation after Thornton and Guza (1983), to demonstrate that the presence of nearshore sediment, in the form of sand waves, offers "natural" protection of the sea cliffs. One mechanism by which sand waves influence the nearshore wave field is by moving the locus of wave energy breaking seaward. Given the shape of the sand wave measured on the Homer beach, the position change of wave break is approximately 70 m seaward – a distance that does not depend upon wave conditions. This behavior is, in essence, a result of temporary beach aggradation, which induces wave breaking further offshore. Another mechanism by which sand waves protect the coast is by changing the wave energy dissipation pattern. Between any two cross shore positions within the surf zone, there will be a decrease in wave energy landward, whether a sand wave is present or not. Our modeling shows that the wave energy flux dissipation is enhanced by nearly 15% by sand waves with geometries similar to those present on the beach on the north shore of Kachemak Bay. Of particular interest is the change in tidal level of optimum dissipation enhancement. Our model results show that during typical environmental conditions for the bay, maximum dissipation enhancement occurs at mid-tide. During extreme events, such as those assumed to cause the most sea cliff retreat, maximum dissipation enhancement occurs at high tide. Importantly, this suggests that the sand wave is most effective at dissipating wave energy, when large erosive events threaten the coast.

Numerical modeling of dissipation suggests that wave energy flux is significantly increased by the presence of intertidal sand waves, like those present along the north shore of Kachemak Bay, inducing wave breaking further seaward from the sea cliff base and expending energy in the turbulent bore. This behavior provides a "natural" buffering for the sea cliffs, and suggests that activities that shut off this sediment supply might enhance sea cliff retreat and decrease inputs to the sediment budget of the Homer spit.

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