Field observation of morpho-dynamic processes during storms at a Pacific beach, Japan: Role of long-period waves in storm-induced berm erosion

By Masaru MIZUGUCHI*1,† and Katsumi SEKI*1,*2

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Abstract: Many ultrasonic wave gages were placed with a small spacing across the swash zone to monitor either sand level or water level. Continuous monitoring conducted for a few years enabled the collection of data on the change in wave properties as well as swash-zone profiles. Data sets including two cases of large-scale berm erosion were analyzed. The results showed that 1) shoreline erosion started when high waves with significant power in long-period (1 to 2 min.) waves reached the top of a well-developed berm with the help of rising tide; 2) the beach in the swash zone was eroded with higher elevation being more depressed, while the bottom elevation just outside the swash zone remained almost unchanged; and 3) erosion stopped in a few hours after the berm was completely eroded or the swash-zone slope became uniformly mild. These findings strongly suggest that long waves play a dominant role in the swash-zone dynamics associated with these erosional events.

Keywords: field observation, berm erosion, sediment transport, long period waves, Hasaki pier, swash process

1. Introduction

1.1 Laboratory studies on cross-shore beach profile change. Cross-shore sediment transport and the resultant beach topography changes have been studied for a long time. Laboratory experiments, conducted extensively, have shown that one could predict beach profile change for a given beach profile (or slope) and incident wave conditions (wave height and period of regular waves) at least qualitatively. For example, see Sunamura (1988),1) where a non-dimensional parameter (Sunamura’s C) to classify the beach profile transformation is proposed. However, the dynamic similarity in the movable bed experiments does not hold in the laboratory and in the field because natural sands (of nearly uniform grain size) were used for the laboratory test with much smaller incident waves as compared with those in the real coast. In addition, most experiments were conducted under regular waves. But some experiments were carried out by applying irregular waves and they indicated that the results of regular wave tests might be applied by using representative values such as the significant wave height and period, but some smoothing of bar profile particularly around the breaking point was necessary (e.g., Otsuka et al. (1984)2) and Mimura et al. (1986)3)). Very few studies have been tried to explore the effect of tides on beach change (e.g., Hattori and Izaki (1981)4)).

Large-scale experiments with irregular waves were also conducted, giving some insight into the real process. The results of the experiments were qualitatively similar to those of small-scale experiments. However, different values for the constant (Sunamura’s C) were needed to classify the expected beach profile changes in the large experiments from those in small laboratory experiments (e.g., Kajima et al. (1982)5)).

Recently, the effect of mixed grain size on beach profile changes stimulated additional research. Coarse sand may be transported onshore, while fine
sand moved offshore. This may give quite a different picture of profile changes in the field (e.g., Tanaka et al. (2000)).

1.2 Field studies on cross-shore beach profile changes. Field observations are crucial for deeper understanding of the coastal process. What are important properties of waves in the nearshore zone (i.e., irregular waves of wide-band spectrum) for sediment transport? How are sediments (of mixed size) transported and how do they contribute to profile changes? Does the tide play an essential role in the process?

In an attempt to resolve these problems, field studies have been carried out in Japan to collect data on topographical change and incident wave properties at a specific site. The earliest study was conducted at the Ajigaura research pier, 200 m long, located on the northern Ibaraki coast. See Hashimoto and Uda (1979, 1982).

The Hasaki observation pier (Photo 1), the research facility of formerly the Port and Harbour Research Institute (PHRI) and now the Port and Airport Research Institute (PARI), is located at a sandy two-bar beach on the southern Ibaraki coast, 70 km east of Tokyo, facing the Pacific Ocean. The length of the pier is 400 m. Analyzing data obtained at the Hasaki pier, Kato and Yanagishima (1988) stated that the shoreline advance steadily under calm wave conditions and the berm receded rapidly during storm events. This statement agrees with the finding in laboratory experiments. However, Kato and Yanagishima (1990, 1993) showed that the rapid berm erosion was closely related to the existence of long-period waves near the shoreline. Howd and Holman (1984) also reported a strong correlation between long-period wave motion and bottom profile change in the swash zone at the Duck pier, North Carolina, USA. Such processes may be difficult to reproduce in laboratory studies.

Shindo et al. (1999) re-analyzed the beach profile data collected through daily sampling at Hasaki by PHRI during the period of 12 years from July 15th, 1986 to July 14th, 1998. They found the presence of a one-year beach cycle which consisted of the rapid retreat of the shoreline during the action of storm waves by typhoons or low pressure systems and the slow advance of the shoreline between storms as shown in Fig. 1 (D.L \pm 0 m = T.P. – 0.687 m). However, the interval between daily samplings of beach profile is too long to explore the dynamics involved in beach changes.

1.3 Purpose of this study. Understandings of the dynamics in the swash zone are of great importance to model the beach response to waves. The swash zone is the most easily accessible place where the observation of large-scale beach changes can be made during a storm. Previous field measure-
ments in the swash zone have only been conducted under non-storm wave conditions where minor beach changes, if any, were observed. For example, refer to Butt and Russell (2000).14)

The present study aims 1) to present field data obtained through intensive and continuous measurements of both waves and swash-zone morphology by deploying many ultrasonic wave gages along the Hasaki observation pier and 2) to elucidate erosional processes occurring in the swash zone, focusing on the erosion of a berm under the action of storm waves based on the data.

2. Data acquisition by old measuring system and their analysis16),17)

In 1999 twelve air-borne type Ultra-Sonic Wave Gages (USWG) were deployed along the Hasaki pier as shown in Photo 2. USWG can detect the sand level or water surface depending on whether water is absent or present. Thus, continuous measurements of both waves and beach profile in the swash zone could be made for years. The gage output was digitized with a time interval of 0.2 s and stored directly to a hard disk in PC. However, a two-year period of trial was required to establish a reliable measurement system. The detail of the measurement system was explained by Mizuguchi et al. (2001).15) This observation system is called the old system because an improved one was introduced in 2002.

An example of data obtained is shown in Fig. 2, in which the channel number denotes the location of gage installation. For those gages located offshore of channel 4 (hereafter “channel” is abbreviated as “ch”), water surface elevations were detected with saw-tooth shaped time series of typical broken waves. For ch.0 and ch.1, no waves reached these locations. For ch.2 and ch.3, the water surface was observed intermittently only when swash waves reached these locations.

The locations of wave gages on the pier are shown in Fig. 3. The twelve gages, including two of PARI, were placed over a cross-shore distance of 60 m. In this figure the beach elevations measured by the wave gages are compared with those measured manually using a lead line on every weekday. The detection of the beach surface from the wave gage data is based on the assumption that the beach was exposed when no significant variation (less than 3 cm) was recorded for the duration of 10 s. The beach elevations measured before (on the 17th and 18th of August 2001) and after (on the 20th) an erosional event show good agreement between the two different measuring methods. The beach profile
based on the wave gage data on the 19th, when the manual survey was not available, lies in the middle.

Storm waves induced by Typhoon 0111 (the 11th typhoon in 2001) attacked Hasaki in the mid to late stage of August 2001. Figure 4 plots the wave gage data at three selected locations. The beach elevation was lowered at ch.0 and ch.1, both located near the shoreward boundary of the swash zone. The bottom diagram in Fig. 4 shows significant wave height $H_{1/3}$ and period $T_{1/3}$ of offshore waves measured at a water depth of 23 m off the Kashima Port. The measuring station lies about 7 km north of the Hasaki pier. An interesting feature is that erosion occurred over a short period (about one hour) with a drop of 40 cm of beach level at a berm (the upper diagram).

Figure 5 shows the beach elevation change for a week during the storm. Small, abrupt erosional events (denoted by “erosion 1” and “erosion 2” in Fig. 5) were observed before the main event (“large-scale erosion”). Each of the erosion events started just before the high tide and stopped during the high tide (and high waves) continued. It is also noted that small accretion was often observed before the erosion events. Wave conditions near the shoreline and offshore are also plotted. In the middle diagram powers of short- and long-period waves, separated by a cut-off frequency of 0.040 Hz, are shown for ch.9 ($x = 56$ m), located just outside of the swash zone at low tide. The magnitude of short period waves fluctuated with the tide level since the magnitude was controlled by depth-limited wave breaking. Offshore wave heights were larger around the midnight from 21st to 22nd than those during the large-scale erosion. However, no erosion was observed probably because there was no berm to be eroded or the swash-zone slope was already sufficiently mild. The bottom diagram shows the angle of incident waves with the dashed line denoting normal incidence to the beach.

Figure 6 shows the power spectra at ch.9 for the three erosion events (erosion 1 and 2, and large-scale erosion) indicated in Fig. 5. The wave power during erosion 1 and 2 was much smaller than that during the large-scale erosion for both short- and long-period waves. It is also seen that the power spectra at the large-scale erosion showed clearer node to anti-node behavior, which is in agreement with that predicted by standing wave theory, up to lower frequency of normal wind waves. This figure also supports the
conclusion that large energy lies in the form of standing waves. For erosion 1 and 2, incoming waves were not sufficient to start significant erosion.

Figure 7 is a magnified plot of the beach elevation change near the shoreline. Nearly simultaneous lowering of the beach elevation occurred in the swash zone, and the higher the initial elevation was, the larger the lowering was. The beach-face slope in the swash zone became milder. The sand transport rate averaged over 10 min. was estimated at ch.3 by applying the continuity equation of sand. Figure 8 shows the estimated rate with a quite large peak value of 0.4 m$^3$/m/min, although this estimate may not be accurate because the distance between the

Fig. 5. Change in beach elevation measured by wave gages for a week of the storm-wave attack (Aug. 17 to 24, 2001), and also in wave powers near the shoreline and offshore wave properties.

Fig. 6. Power spectra of waves near the shoreline (ch.9). Three smooth lines denote relative amplitude variations of standing waves.
The results presented in Figs. 4 to 7, provides an interesting picture of berm erosion processes: how it starts and ends. A further examination will be made in the following with a more convincing data set.

3. Analysis of data acquired by new measuring system

In July 2002 a new observation system was deployed by increasing the number of wave gages from twelve to twenty. Some gages were installed well landward of the average shoreline to cope with large run-up during storms. Gages in the swash zone were placed with a smaller spacing of about 3 m. These two improvements made it possible to estimate the sand transport rate more accurately. The new gage locations are shown in Fig. 9, and also plotted are beach profiles for the erosion period to be analyzed later.

The time history of the front face of the bore is calculated from the wave gage data. Two most seaward dry points are used to obtain a linear beach profile and two most shoreward wet points are used to estimate the water surface profile. The intersection of the extended profiles gives the swash front. An example is given in Fig. 10. The calculated swash front forms an envelope of the measured surface profiles as expected; however, a considerable difference between the calculation and the measurement is found at some points in Fig. 10, such a discrepancy being ascribed to the presence of turbulent water surface near the swash front. It is also apparent that only long-period swash is significant and the magnitude (wave height) of the long-period waves are of the order of 1 to 2 m as is also seen in Fig. 4.

Storm waves induced by Typhoon 0315 attacked Hasaki in mid to late September 2003 and severe shoreline erosion occurred. Figure 11 shows the change of beach elevation at the gage locations for eight days, including the erosion period in the middle of the top diagram, wave conditions measured at the most shoreward submerged location, that is ch.16 (z = 61.4 m), and offshore wave properties (wave height and period, and wave direction) measured off
the Kashima Port. Long-period waves are separated by applying a low-pass filter with a cut-off frequency of 0.040 Hz, the same frequency as used before (Fig. 5).

Waves were calm on the 18th and 19th of September and no significant beach profile change was observed, although small accretion was seen at the toe of berm (ch.10 and its offshore portion) at high tide. Power of long-period waves was negligibly small. Power of short-period waves fluctuated with the tide, as the height of broken waves may be limited by water depth. Around the midday of the 20th, power of short-period waves increased considerably and some decrease in beach elevation was observed at the toe of the berm. Again in the afternoon of the 21st, a larger decrease was observed just below the berm top with the occurrence of large power of short-period waves. In this stage, the beach elevations near the berm top slightly increased, resulting in berm growth. Because the wave gages
did not record significant swash waves there, the increase in elevation was likely to be brought about by wind blown sand.

Rapid erosion of the overall berm occurred in the morning of the 22nd during rising tide, while powers of both short- and long-period waves increased dramatically. Unfortunately, the most shoreward wave gage was not located in the area of no topography change. After the main erosion, only small fluctuations of beach elevation change were observed at high tides.

Figure 12 illustrates the hourly change of beach profile plotted for the duration of 8 hours of the main erosion. The most shoreward point of no change is again based on the data of routine daily survey. As already noticed in Fig. 11, the erosion started in the lower part of the berm profile as the tide rose. In the early stage of the erosion, the foreshore immediately below the berm top retreated, its slope being kept steep (0.06) or becoming steeper. Once the swash reaches the berm top, erosion proceeded to lower the beach elevation over the entire berm area. The erosion stopped when the berm profile disappeared completely. After the erosion, a wide swash zone with a mild slope of 0.02 appeared.

The net volumetric (including void) sand transport rate per hour is calculated and plotted in Fig. 13. During the main erosion the sand was transported offshore across the entire swash zone. The offshore transport rate increased in the offshore direction in the swash zone, the increase being at maximum in the middle of the swash zone and slower both inner and outer swash zone. This corresponds to a decrease in beach elevation with more depression in higher elevation in the berm area. The transport rate is almost constant seaward of the swash zone. No profile change occurred there, as seen in Fig. 12. The
sand transport rate at ch.10 (Fig. 13) can be defined as the amount of sand lost from the swash zone to the offshore. The maximum transport rate there was 12.5 m$^3$/m/hr and is half of the ten-minute average value calculated for the case of Typhoon 0111 described previously.

4. Berm erosion process

4.1 How does the large-scale erosion start and stop? First, we look into the wave differences before, during, and after the erosion by calculating the phase relation between the swash oscillation and the waves just outside the swash zone. Figure 14 shows that, before the erosion, the phase between the swash and the waves near the shoreline is clearly 0, which indicates that waves are of pure standing waves in the frequency range of $f = 0 - 0.028$ Hz. However, after the erosion, the phase 0 holds only in very low frequency and the shift to $\pi$ is more gradual at a lower frequency of 0.020 Hz. This may be interpreted as the reduction of reflectivity of the beach with the swash-zone slope becoming milder. It is noted here that the early shift to $\pi$ results from the larger distance from the measuring point to the shoreline which retreated during the erosion. Seki and Mizuguchi (2004) proposed a model to separate the shore sand transport with the slope effect because waves themselves are symmetric in run-up and run-down. On the other hand, breaking waves (or of progressive mode) might provide larger sand transport during the onshore (or run-up) phase with larger velocity (and strong turbulence) than the run-down phase. High waves without significant power in long-waves are rarely observed at this site; such waves, in our speculation, should contribute to onshore sand transport, developing a berm. The effect of a tide may be considered to be just a static change of the mean sea level, as the time scale of swash morpho-dynamics is of the order of long-period waves and is much shorter than the time scale of tidal fluctuations. It is plausible that long waves of standing mode, which are not large enough to reach the berm top even with the help of rising tides, cause erosion of the beach face below the berm crest to form a scarp, which may retreat gradually.

It is found that erosion stops while the tide still rises and high power of swash waves continues. This leads to an idea that erosion ceases when sand transport reaches dynamic equilibrium between the asymmetric swash motion for net onshore transport and the slope effect for net offshore transport as the slope becomes milder and the swash becomes more bore-like features. However one can also argue that erosion simply stops when the berm disappears.

4.2 Sand transport rate for different time scale. As shown in Fig. 15, the sand transport rate for one hour differs considerably with the different reference time and the hourly values do not behave as may be expected from the wave properties estimated hourly. Figure 16 shows that sediment transport rate calculated for 10 min. fluctuates considerably. The maximum value is 0.5 m$^3$/m/min or 30 m$^3$/m/hr, slightly larger than that plotted in Fig. 8.
It is observed in both cases presented here that a small number of long-period (1 to 2 min.) swash waves with an amplitude of 1 to 2 m play a predominant role in the erosion process. The erosion in the swash zone occurs within a few hours when the long-period waves are dominant. The number of long-period waves of significant magnitude may be less than 100 as seen from Fig. 4. The net transport rate by a single swash wave may be large enough to be estimated, but this is beyond the scope of this study.

5. Conclusions

With the purpose of elucidating the cross-shore beach process, intensive and continuous field measurements were conducted for a few years by deploying many ultrasonic wave gages placed with a small spacing in the swash zone. Precise data on the sand elevation and the water level were obtained. Analyses of the two data sets of large-scale (berm) erosion led to the following results:

1) Shoreline erosion started when high waves with significant power in long-period (1 to 2 min.) waves reached the top of a well-developed berm with the help of rising tide.

2) During the erosion, beach elevation in the swash zone decreased with higher portion being lowered more. The bottom elevation just outside the swash zone remained constant. The maximum ten-minute averaged transport rate was 0.5 m$^3$/m/min.

3) The erosion stopped in a few hours when the berm was completely eroded and the swash-zone slope became mild.

From these results we speculate that the erosion is caused by long-period standing waves on the steep foreshore slope, and stops when the mild slope and (partially) breaking waves provide dynamic equilibrium for sand transport in the swash zone. The presence of long-period waves is a dominant factor controlling swash-zone dynamics at this field site. However it is not yet clear if long-period waves are absolutely necessary for a berm to be eroded because no storm waves without significant magnitude of long-period waves have been observed at Hasaki.

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