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Shoreline change caused by the increase in wave transmission over a submerged breakwater due to sea level rise and land subsidence

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ABSTRACT

Sandy beaches protected by submerged breakwaters, which have crests below sea level, are assumed to be vulnerable to relative sea level rise (SLR). In this study, the shoreline change due to sea level change and land subsidence along the Niigata West coast in Japan, which is protected by submerged breakwaters, was investigated using field data and a shoreline prediction model assuming that the shoreline change is caused by cross-shore sediment transport. The shoreline movement in the past 10 years was not directly caused by sea level change and land subsidence. However, our model predicts that over the next 100 years, the shoreline will retreat 60 m owing to the increase in the energy flux of incoming waves over the breakwater caused by SLR and land subsidence. These results imply that other sandy beaches protected by low-crested breakwaters as well as those behind coral reefs, which are natural submerged breakwaters, would experience non-negligible erosions caused by future relative SLR.

1. Introduction

Many sandy beaches in the world globally are eroding because of various natural and anthropogenic causes including reduced sediment supply from rivers and unbalanced longshore sediment transport rates around coastal structures. Countermeasures against beach erosion are classified into soft solution, which includes beach nourishment and sand bypassing, and hard solution, which includes groins, detached breakwaters, and submerged breakwaters (Komar, 1998).

Unlike detached breakwaters, submerged breakwaters do not interfere with the view of the horizon from the shore; therefore, submerged breakwaters are sometimes constructed as countermeasures against beach erosion where the availability of sediments for nourishment is limited and tourism is prevalent. However, because the crests of submerged breakwaters are below sea level, projected sea level rise (SLR) and land subsidence will lead to decreased wave energy dissipation by submerged breakwaters, causing instability in the sandy beaches. Thus, sandy beaches behind submerged breakwaters are vulnerable to SLR and land subsidence.

Moreover, whether a sandy beach is protected with coastal structures or not, according to the Bruun Rule (Bruun, 1962), the shoreline of the beach is expected to retreat owing to the seaward sediment transport caused by the upward and shoreward shift of the equilibrium beach profile due to relative SLR. Using long-term data of shoreline position and sea level along the East Coast of the USA, Zhang et al. (2004) showed that the rate of shoreline retreat is highly correlated with that of SLR. List et al. (1997), on the other hand, reported that along the Louisiana coasts, USA, no correlation was found between the amount of shoreline retreat estimated by the Bruun Rule and that of SLR. This suggests that the SLR-induced shoreline change is caused by the mechanism assumed in the Bruun Rule as well as other mechanisms including sediment transport to/from dunes and offshore regions as suggested by Stive (2004); Davidson-Arnott (2005) and others.

To predict shoreline changes caused by SLR, Karambas (2003) calculated the amount of shoreline retreat induced by several values of SLR ranging from 0.25 to 1.0 m using a process-based one-dimensional model, which predicts beach profile change by estimating the cross-shore variation of cross-shore sediment transport rate and was validated against experimental data. Cowell et al. (2006) estimated the probabilities of the amount of future shoreline changes on the Manly and Mission beaches in Australia using a profile translation model. Ranasinghe et al. (2012) developed a shoreline prediction model that calculates the dune erosion caused by wave run-up and stochastically predicted the amount of shoreline change by 2100 on Narrabeen Beach in Australia using storm time series that were probabilistically produced. Future shoreline changes from 2008 to 2095 on the Hasaki coast in Japan facing the Pacific Ocean were estimated by Banno and Kuriyama (2014) using their shoreline prediction model and considering SLR and wave climate change under two scenarios.

While a number of studies investigated the impact of SLR on natural beaches, research on the effect of SLR on beaches protected by coastal

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structures including submerged breakwaters is rare. Yet even when coastal structures successfully protect the beaches behind them as expected, these beaches that were subjected to erosion in the past may still be at risk of erosion. Hence, examining shoreline changes caused by relative SLR on a sandy beach protected by submerged breakwaters can provide important information for beach conservation strategies. Moreover, the investigation results may also be helpful for preserving healthy beaches behind coral reefs, which form natural submerged breakwaters.

The objective of this study is to predict the future shoreline change caused by SLR and land subsidence along the Niigata West coast in Japan, which is protected by submerged breakwaters and is now experiencing land subsidence. First, the influences of sea level change and land subsidence on the shoreline change during the 10-year period from 2001 to 2011 is investigated. Then, the future shoreline change during the 100-year period from 2011 to 2111 is predicted using a shoreline prediction model.

2. Study site

2.1. Outline of the Niigata West coast

The Niigata West coast is located in central Japan and faces the Sea of Japan (Fig. 1). The coast was developed by the sediments that were discharged from the Shinano River and transported by the predominant westward longshore current. Because of the decrease in sediment discharge and the interruption of longshore sediment transport caused by river improvement (1875–1903), jetty construction (1987–1924) and openings of Ohkouzu and Sekiya diversion channels (1922 and 1972, respectively), the study coast as well as the coasts west of the study site suffered beach erosion since the 1910s (e.g., Kuriyama et al., 2006). In an effort to stop the erosion, detached breakwaters were constructed since the 1950s. Although they have protected the beaches behind them, erosion seaward of the breakwaters continued.

To prevent the offshore erosion, submerged breakwaters were constructed since 1989 approximately 350 m offshore of the detached breakwaters (Fig. 2). The cross-shore width of the submerged breakwaters is 40 m, and the crown height is approximately 2.5 m below the low water level. In addition to the submerged breakwaters, groins were also constructed since 1988 to reduce the alongshore current velocity shoreward of the submerged breakwaters.

Fig. 1. Map of Japan showing the location of the investigation site.

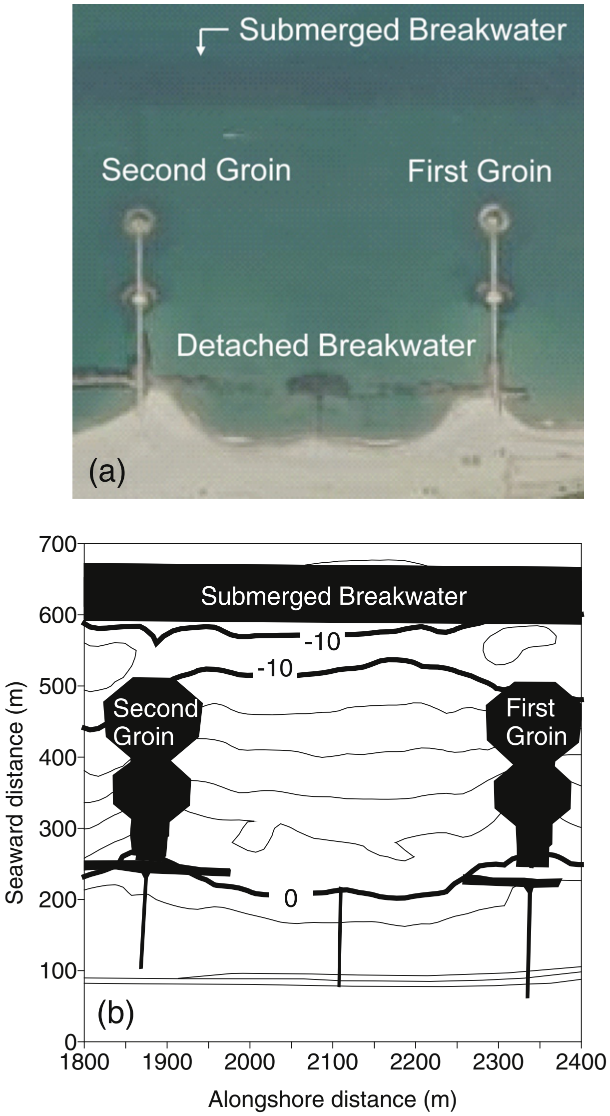

Fig. 2. (a) Aerial photograph taken in November 2007 and (b) morphology in July 2011 in the investigation area. Contours (m) are drawn at 2-m intervals in panel (b).

The investigation area lies between the two groins shown in Fig. 2. A total of 200 m of previously constructed detached breakwaters was removed in 1995 and 1996. In 1996, a submerged groin with a crest height of 4.9 m below the low water level was constructed between the tip of the second groin and the submerged breakwater. A beach nourishment of 427,000 m^3 of sand was implemented during 1994–2000. Detailed information on the beach nourishment and coastal structure construction is shown in Kuriyama et al. (2006).

The median sediment diameter in the foreshore of the investigation area was 0.15–0.30 mm according to field surveys on sediment size conducted once a year from 2003 to 2011.

2.2. Morphological change

Based on the morphological data obtained approximately twice a year, the shoreline position defined at $z = 0.5$ m (z is the elevation according to the datum level) averaged alongshore in the investigation area moved shoreward from 2001 to 2007, and has been stable since 2007 (Fig. 3(a)). Because the investigation area was surrounded by the two groins extending to where the elevation was about -10 m