Comparison between Longshore Sediment Transport Due to Waves and Long-term Shoreline Change in Majuro Atoll, Marshall Islands

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Abstract

Topographic changes in Majuro Atoll, Marshall Islands, are caused by various natural and artificial processes, for example, sediment transport induced by waves and currents, sediment supply from coral reefs, and the existence of constructed structures along the shoreline. For the present paper, numerical calculations of wave transformations of the lagoon of Majuro were carried out, and wave energy fluxes, which are the potentials of alongshore sediment transport, were also estimated. The waves in the lagoon were assumed to be generated in two ways: wind waves and diffracted waves from swells. The contribution of waves to topographic changes in Majuro were estimated by comparison with the process of past topographic change, which was obtained by satellite imagery.

Key words: diffracted waves, lagoon-side coast, Majuro topographic change, wave energy flux, wind waves

1. Introduction

In the Pacific Ocean there are many atolls on which often appear very low and narrow islands, which are called atoll islands. Coastal sediments of atoll islands consist mostly of dead foraminifers and coral and shell fragments since the coasts of atoll islands have no rich sources of sands such as rivers.

On such coasts of atoll islands, there should exist a sediment supply process from the reef edge to the shoreline due to biological sediment production of reef-building organisms, in addition to cross-shore and alongshore sediment transportation processes due to nearshore waves and currents. Since the biological sediment supply process is too complicated to be measured quantitatively, the biological process and the interaction between the biological and the physical processes have not been analyzed quantitatively so far. These processes play a crucial role in the morphological changes of atoll islands over the long term. In particular, the rising sea-level will be one of the most notable impacts of global climate change on atoll coasts in the near future (Letherman, 1977). Thus we have to take this into account in developing strategies for adaptation to future environmental changes on atoll islands.

In the present study, field measurements and numerical calculations were carried out at Majuro atoll in the Marshall Islands, in order to investigate the interactions between the wave field in the lagoon and shoreline changes on the lagoon-side coast. Majuro atoll is located at 17°22′E, 7°6′N, and is the capital of
the Republic of the Marshall Islands is located (Fig. 1). In field measurements, we carried out inspections of coastal sediments and beach profile surveys, as well as continuous observations of bottom velocities along the lagoon-side coast using self-recording velocimeters.

2. Coasts at Majuro Atoll

Field measurements were carried out from September 14 to 26, 2003, at Majuro atoll. Figure 1 shows an outline of the atoll. It is 40 km long in the longitudinal direction and 9.7 km wide in the latitudinal direction. The area of the lagoon is 324 km$^2$, with an average depth of 46 m. The lagoon is surrounded by reefs, except for the north passage as shown in Fig. 1 (Xue, 2001).

In the southern part, one atoll island, Long Island, stretches from Rita, on the eastern end in Fig. 1, to Laura, on the western end, while small islets stud the northern part. Rita and Uliga are densely populated and highly urbanized districts of the atoll. Ports and harbors have been constructed on the coasts of those districts. On the other hand, Laura is a less urbanized district, where the traditional life-style seems to continue.

When we saw the coast along Long Island, artificial vertical seawalls seemed to cover almost all the coast around Rita and Uliga. Ships and boats were moored in the ports and harbors, and no sandy beaches could be seen, as shown in Fig. 2. Approaching Laura along Long Island, we could see sandy beaches, the width of which became broader and broader as shown in Figs. 3 and 4.

We carried out beach profile surveys at lines No. 1 through 5 shown in Fig. 1. The profile survey ranged from shoreline areas to reef edges on both lagoon-side and ocean-side coasts. The results of the survey show that the reef area where water depth is less than 1 m extends offshore for 200-400 m, and that the water depth suddenly increases beyond the reef edge. The measured profile at line No. 2 in Fig. 1 is shown in Fig. 5. Water depths near the shoreline up to 200 m on the horizontal axis were obtained using the ordinary surveying equipment (Fig. 6). In deeper areas, we used a fish-finder attached to a boat to detect the sea bottom. Sandy beaches and sandy sediments on the reef were found on the lagoon-side coasts, while there were few sandy sediments on the ocean-side. This suggested the existence of alongshore sediment transport due to waves and nearshore currents.

According to Xue (2001), coastal erosion damaging Majuro for 50 years since World War II has brought about shoreline regression by about 10 m on both lagoon-side and ocean-side coasts. In particular,
severe erosion was found on the lagoon-side coast of Uliga and the tip of Laura islet. Xue (2001) pointed out that the construction of artificial coastal structures such as vertical seawalls and dredging of the reefs were the main causes of coastal erosion, and that blocking the flow across the island due to construction of causeways was also a cause of erosion. The existence of alongshore sediment transport from Uliga to Laura is also indicated in Xue (2001).

3. Detection of Coastal Changes

A map surveyed in 1944, in aerial photos taken in 1983, and a satellite image (IKONOS) taken in October 2000 were used in detecting long-term coastal changes in Majuro over the last several decades. Changes in shoreline positions between 1944 and 1983 were based on 1:25,000 maps prepared by Manoa Mapworks (1989) who revealed shorelines at mean sea level using aerial photographs in 1944 and 1983. The maps were scanned at 300 dpi resolution and were georeferenced to the 2000 IKONOS image using ERDAS Imagine version 8.7. We used a 4-m resolution IKONOS multispectral image to detect the shorelines in 2000. Using values of the near infrared (NIR) band of the IKONOS data, we excluded water areas and estimated the shoreline positions at the IKONOS image acquisition time, as wavelengths in the NIR region are strongly absorbed by the water column. Then we performed contextual editing to exclude areas of subaerially exposed reef flats that had high NIR values. Finally, considering the slope angles of beaches estimated by the field survey, we obtained the shoreline positions at mean sea level. The areas bounded by the shorelines were converted to polygon data and were overlayed using ArcView version 3.2 to detect changes over time. Yamano et al. (submitted) describes these processes in detail.

Figure 7 shows the eroded and accreted areas detected by comparing the IKONOS image in 2000 and the map in 1944. This figure indicates that the tip of Laura islet has been eroded and the lagoon-side coast of Laura has accreted during the period. The coasts of Long Island are dotted with both eroded and accreted...
areas, thus no apparent erosion or accretion area were detected. The some small accreted areas along Long Island may be due to the causeway.

The other comparisons between the map and the aerial photos, and between the aerial photos and the satellite image yielded no apparent areas of erosion or accretion. The results shown in Fig. 7 may include errors due to the geometric correction of each image and the shoreline determination (Yamano et al., submitted). Thus it is quite difficult to determine precisely the magnitude of the shoreline retreat and advance. However, trends in erosion and accretion were reasonably detected through the comparison.

4. Calculation of the Wave Field in the Lagoon

We calculated wave transformations numerically in the lagoon of Majuro, in order to verify whether lagoon-side coastal changes had been due to waves incident from the lagoon. In this study, waves in the lagoon were assumed to be generated by the wind blowing in the lagoon or by diffracted swells entering through the northern passage. These two kinds of waves were simulated with wave and wind climate data by appropriate numerical models.

4.1 Wave and wind climate data at Majuro

Figures 8 and 9 show wind speed and direction data at 12 hour intervals, which were extracted from hourly data observed at Majuro Weather Station from January 2002 to September 2003. The wind direction was measured in degrees clockwise from true north. These figures indicate that northeastern or eastern trade winds blowing at a speed of 4 to 5 m/s are predominant in winter, around January, and that no dominant wind direction is found in summer, around September, since the trade winds become weaker.

Figures 10 and 11 show monthly-averaged significant wave heights and mean wave directions of wind waves and swells, respectively, around Majuro from 1990 to 1999, which were obtained from the ECMWF (European Centre for Medium-Range Weather Forecasts). These figures indicate that both the heights of wind waves and swells become larger in winter when the trade winds predominate and the directions are south for the wind waves and northeast for the swells. On the other hand, the height of both waves becomes smaller in summer.

4.2 Wave height and direction of wind waves

The waves generated in the lagoon were simulated by the SMB (Sverdrup, Munk, Bretschneider) method.
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(Bretschneider, 1958). In the SMB method, significant wave height, $H_{1/3}$, and significant wave period, $T_{1/3}$, are estimated according to wind speed at 10 m above sea level, $U_{10}$, and the fetch, $F$, using the following equations (Wilson, 1965).

$$\frac{g H_{1/3}}{U_{10}} = 0.30 \left[ 1 - 0.004 \left( \frac{g F^{1/3}}{U_{10}} \right)^2 \right]$$

$$(1)$$

$$\frac{g T_{1/3}}{2zU_{10}} = 1.37 \left[ 1 - 0.008 \left( \frac{g F^{1/3}}{U_{10}} \right)^2 \right]$$

$$(2)$$

Three cases of wind speed on the lagoon were assumed as 6, 4 and 2 m/s, since the average wind speed at Majuro was about 4 m/s as shown in Fig. 8. For each case, three cases of wind direction were assumed as eastern, northeastern, and northern, since the dominant direction measured at Majuro was northeastern as shown in Fig. 9. The effective fetches for each wind direction at points along the lagoon-side coast were measured using a nautical chart.

Figure 12 shows the distributions of significant wave heights along the lagoon-side coast, calculated for the three wind directions and for a wind speed of 4 m/s on the lagoon. The horizontal axis ranges from Uliga to the tip of Laura islet along the lagoon-side coast. The numbers put on the axis correspond to those of the surveying lines shown in Fig. 1. Figure 12 shows that the wave height at Laura becomes maximum when waves in the lagoon are generated by an eastern wind and minimum for a northern wind. However, the wave height at Uliga becomes maximum for a northeastern wind because the shape of Majuro atoll gives rise to a sheltered area around Uliga. The reason wave heights are relatively low on the coast between Nos. 3 and 4 is that a shallow water area and two groins located on the coast, as shown in Fig. 1, act as breakwaters for the coast.

4.3 Wave height and direction of diffracted waves

The average water depth in the lagoon is about 46 m and the lagoon is surrounded by a sheer cliff of coral reefs. Thus, the dominant transformation of the waves incoming through the northern passage can be assumed to be wave diffraction, where wave refraction and shoaling are relatively neglected. In the present study, the wave height distribution along the lagoon-side coast was calculated by the boundary integral method (Lee, 1971), applying the Green’s theorem to the Helmholtz equation, which was the governing equation.

The boundary elements were set along the lagoon-side coast and across the northern passage. The length of the boundary elements were set at 500 m for the passage and 1,000 m for the coast, respectively. Since the length of elements had to be set longer than desirable due to numerical restrictions, the period of incoming swells also had to be set longer than the observed one, so that the wave direction along the coast could be estimated accurately. The height and period of incoming swells were set 1 m and 20 s respectively. The calculations were carried out for the three cases of incoming wave direction, eastern, northeastern, and northern. The boundary condition along the lagoon-side coast was set as a vertical seawall with no water exchange across the boundary, whether or not an atoll islet existed on the reef.

Figure 13 shows the calculated wave heights and directions on the lagoon-side coast for a northeastern incoming swell. In the figure, the angle of wave direction of 90 degrees indicates waves entering normal to the coast: a direction angle of less than 90 degrees indicates waves going toward Laura, and of more than 90 degrees, toward Uliga. The wave heights become larger between Nos. 3 and 4 because the area is located in front of the northern passage. The wave directions on the Laura coast are toward the tip of Laura but those on the Uliga coast are the opposite.

4.4 Wave energy flux along the coast

Wave energy flux at the breaking point is an important quantity since it can be proportional to the alongshore sediment transport rate for general conditions (e.g., Inman & Bagnold, 1963; Komar & Inman, 1970). In this study, wave energy fluxes were calculated according to wave heights and directions estimated on the coast. Figure 14 shows the alongshore
component of wave energy fluxes on the lagoon-side coast: the solid line indicates fluxes based on wind waves generated by a 6 m/s northeastern wind, and the broken line, those based on diffracted waves of the northeastern swells. The positive value of the energy flux component indicates that the direction of the flux is from Uliga to Laura.

In Fig. 14, the energy fluxes toward Laura, calculated for diffracted waves become larger in the area between Nos. 3 and 4. The magnitude of wave energy fluxes of diffracted waves is larger than that of wind waves in the area, but, the area is limited in scope to only in front of the passage. On the other hand, the energy fluxes calculated for wind waves change their direction around No. 4. This may correspond to the accreted area on the lagoon-side coast of Laura shown in Fig. 7. The eroded areas along Long Island shown in the figure are also explained by the energy fluxes of the wind waves.

The energy flux results indicate that waves generated by winds are more effective at producing topographic changes in Majuro atoll, comparing the eroded and accreted areas in Fig. 7, even though the magnitude of fluxes are larger for the diffracted waves.

5. Concluding Remarks

In the present study, a field investigation and numerical calculations were carried out in order to clarify the relationship between waves in the lagoon and topographic changes on the coast of Majuro atoll. The discussions lead to the following conclusions:

- Comparisons of the map and the IKONOS satellite image indicate that the tip of Laura islet has been eroding and the lagoon-side coast has been accreting for about 50 years.
- Numerical simulations of the wave field in the lagoon indicate that the distribution of wave energy fluxes based on wind waves agree with the distribution of eroded and accreted areas better than those based on the diffracted waves of swells.

In order to estimate the shoreline change due to waves and currents more accurately, cross-shore topographic changes should be considered: Dean’s equilibrium profile and its modifications adjusted to coral reef beaches (Cowell & Kench, 2001; Kench & Cowell, 2001). Also, estimation of the biological sediment production rate was not dealt with in this study. Future research will need to address these in order to develop a long-term model to simulate maintenance systems of atoll islands.

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