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Reef Rip Current Generated by Tide and Wave during Summer Season: Field Observation Conducted in Yoshiwara Coast, Ishigakijima, Okinawa, Japan

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Abstract. In 2004 and 2005, five drowning accidents in Ishigakijima, Okinawa were documented by Japan Coast Guard and were found to be caused by a strong offshore current commonly known as “reef current”. This type of current has been identified to be responsible in generating the circulation of water and transportation of sediment in coral reefs. In this paper, however, high-speed offshore current in coral reefs is specifically referred to as “reef rip current”. Considering that the generation mechanism of reef rip current is not revealed yet, the researchers conducted a hydrodynamic study in Yoshiwara Coast, Ishigakijima, Okinawa in two phases (normal and storm conditions) during summer season to determine the location and time of occurrence of the strong offshore current that will significantly address safe utilization of coral reef and carbonate beach thereby reducing drowning accidents. The nearshore hydrodynamic project that was undertaken included field measurement of wave, current and tide during normal and storm conditions with the implementation of bathymetry survey by laser method. The results revealed the maximum 20-minute average offshore velocity at 1.2m/s. In addition, it was observed during low tide condition that most of the water inside the lagoon is only discharged through the reef gap.

Key words: Reef rip current, tide and wave dominated, coral reef, safe utilization, water circulation

Introduction

Coastal areas in tropical and subtropical regions are characterized by coral and normal sandy beaches that are attractive for tourists around the world thus making beach and marine tourism one of the fast growing economic industries. On the other hand, utilization of beaches also poses a risk on the safety of the coastal users who are not familiar of nearshore current system. Hence, field study and analysis of drowning accidents in carbonate beach and coral reef have been implemented and conducted in Japan’s subtropical region, Okinawa Prefecture particularly in Yoshiwara coast, Ishigakijima in order to establish and describe the strong offshore current mechanism.

Monismith (2007), Kench et al. (2006), Tamura et al (2006), Hearn (2001, 1999), Nadaoka et al. (2001), Yamano et al. (1998), Kraines et al (1998), Symonds et al. (1995), Gourlay (1994), Young (1989), Roberts et al. (1975) among others have studied and made scientific publications on hydrodynamics in coral reefs in tropical and subtropical regions. However, the impact of nearshore current on safe utilization of carbonate beach and coral reef has not been fully established yet. Literatures have revealed that circulation in reef systems is typically driven by a combination of tidal flow, wind-driven flow (Yamano et al. 1998) and flow induced by the breaking of wind-waves on the reef flat (Kraines et al. 1998; Symonds et al. 1995; Hearn and Parker 1988; Nadaoka et al. 2001) and that currents and deepwater waves are significantly modified by reef morphology (Roberts et al. 1975) in a consistent manner dependent on tidal elevation, reef elevation, and reef width (Kench et al. 2006). Currents on the fore-reef shelf exhibit a distinct periodicity near the diurnal tidal frequency wherein the characteristic of the deep (21m) shelf margin is rather unidirectional (Roberts et al. 1975; Kraines et al. 1998) and high-velocity flow (>50cm/s), but on the shallow shelf, a weaker (5-7cm/s) and more directionally variable currents are found (Roberts et al. 1975). During a typhoon, abrupt decrease and increase of the water temperature with a resultant of about 10C lower than before was documented in the study by Nadaoka et al. (2001). The numerical simulation of Tamura et al. (2006) which showed good agreement with the observed data revealed that currents have an appreciable magnitude of tide-averaged velocities, even during neap tides, which are governed mostly by wave set-up effects.

In this study, however, the relationship and impacts of nearshore hydrodynamics to safe utilization of carbonate beach and coral reef are the key issues.

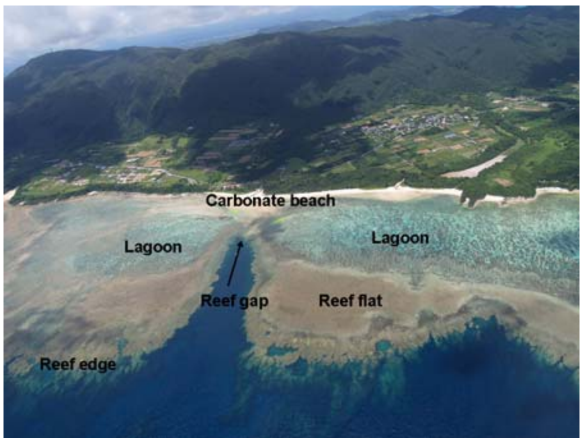

Figure. 1. Aerial view of study site in Yoshiwara Coast

Materials and Methods

A nearshore hydrodynamic project was carried out in Yoshiwara, Ishigakijima's carbonate beach and coral reef coast (Fig. 1) in two phases; Phase 1 was performed during normal condition (small wave and tide dominated) and Phase 2 during storm condition (high wave and tide dominated). The project was implemented in summer season from June 25 to July 25, 2006, the period when the occurrence of drowning accidents had been reported.

An aerial laser survey was conducted for two days by an airborne team from the Sixth Region of Coast Guard in Hiroshima on the actual study site to produce the bathymetry map with high resolution (Fig. 2).

Parameters such as water level, wave height, wave period, water temperature, current and wind speed and direction both in Phase 1 (June 25-July 1, 2006) and Phase 2 (July 1-25, 2006) conditions were obtained through field measurement with the aid of field equipment such as wave gages, electronic current meters (ECM), ADCP, tide gages, thermometer, GPS floats, and anemometer as well as fluorescent dye experiment. These data parameters were analyzed to describe further the wave, tide and current patterns occurring and behaving in coral reef and carbonate beach and consequently to establish their respective relationship.

Results and Discussion

Morphology

The aerial laser survey that produced the bathymetry map in Fig. 2 shows a developed reef flat and lagoon system. The offshore length of the reef system is more than 1,000 meters. Profiles of the reef gap area and the well-developed reef flat and lagoon indicated by transect lines 1 and 2 respectively are shown in Fig. 3. The cross-section along transect line 1 passing thru the reef gap area spans a 250m length of horizontal flat and gradually drops to a depth more than 40m. However, the well-developed cross-section of the reef flat and lagoon indicated by transect line 2 extends a 920m horizontal flat and abruptly drops to a depth more than 40m. Carbonate beach is also developed at the mouth of the river and reef gap boundary. There are also narrow channels that are directed toward the reef gap.

Nearshore wave and current are governed by hard bottom reef geomorphology. In general, incident high wave dissipates its energy over a reef edge and flat depending also on tidal level, i.e., the ratio of waterdepth to wave height. The current in reef lagoon may become weaker but will be faster near the reef gap (locally called "mouth of the coral reef" in Okinawa) which is the location where there is significant geomorphological feature to control the current system inside a reef. Geomorphology of coral reef is the fundamental information to estimate wave and current system, and to justify its safe utilization.

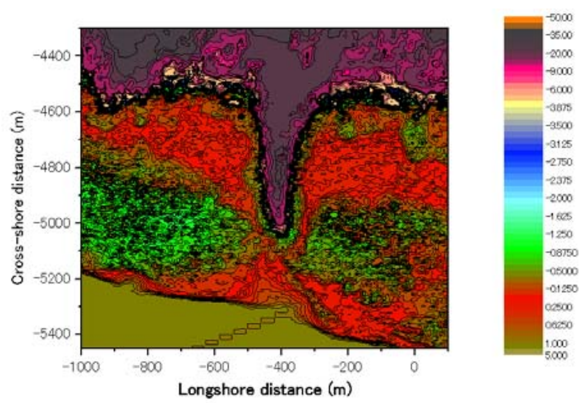

Figure 2. Bathymetry of study area (Yoshiwara coast, Ishigaki, Okinawa Prefecture)

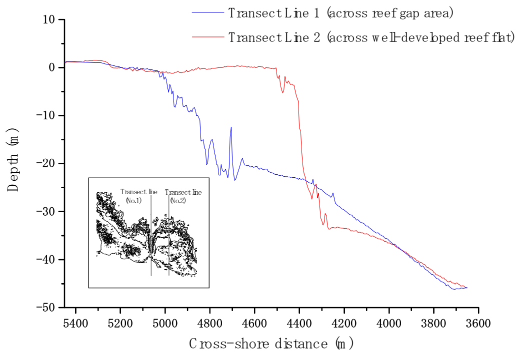

Figure 3. Cross-shore profile of the study area at the reef gap and reef flat (Yoshiwara coast, Ishigaki, Okinawa Prefecture)

Flow visualization by dye and GPS floats

Nearshore current system can be visualized with the aid of dye experiment and GPS floats. Figure 4 shows the point of application of the dye (Pt. A) and its diffusion pattern. The width of the dye is an indication of the strength of the offshore flow which increases in speed as it approaches the reef gap (Pt. B, about 250m in length). As offshore flow moves out from the reef gap, its speed starts to slow down as the flow continues to pass through a much wider cross-sectional area (Pt. C). This is visually represented by the diffusion of the dye which also describes the flow pattern direction.

Figure 5 also shows the flow pattern inside and outside of coral reefs, especially around the reef gap. Small GPS floats originally developed for a study on rip current on sandy beach by Nishi et al. (2003) were applied. The GPS floats are intended to provide direction flows of major and minor currents starting from the points of application from the sandy beach through the reef gap and offshore as represented by Path Lines 1-5 (Fig. 5). Another direction flow mechanism was also applied in conjunction with the GPS floats by a drifter having a GPS gadget that moved in the direction of the current flow (Fig. 5, labeled as staff with GPS) to verify and substantiate flow pattern characteristics and measurements converging through and diverging from the reef gap.

Velocity of a reef rip current

One week duration of nearshore hydrodynamic observation was first conducted from June 25 to July 1, 2006. Figure 6a shows the change in water level inside the lagoon. The tide shows semidiurnal variations. The maximum water level reached up to 2.4m and minimum water level at 0.8m with a tidal difference of 1.6m. The second observation was conducted from July 1-25, 2006 in the presence of storms where maximum and minimum water levels were recorded at 2.5m and 0.75m respectively (Fig. 6b) which resulted into a slightly higher tidal difference at 1.75m.

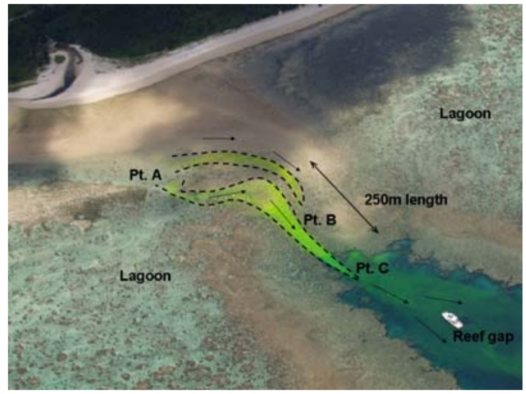

Figure 4. Dye experiment (dye pattern shows an offshore current toward a reef gap)

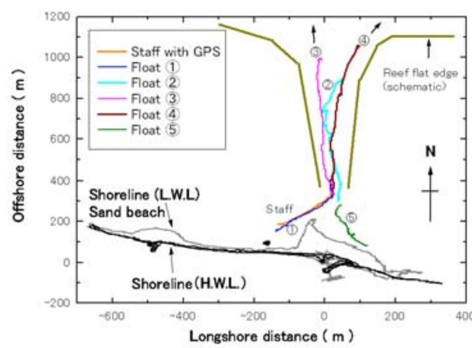

Figure 5. Offshore flow pattern starts from the carbonate beach and moves outside the coral reef through the reef gap

The 20-minute average velocity record in the narrow channel near the reef gap (Fig. 7a) indicates high offshore velocity up to 1.2m/s at ebb tide and reasonably high onshore velocity up to nearly 0.7m/s at flood tide during low tide conditions. The reason for this is attributed to reef edge and reef gap which entrap the water inside the lagoon and outside the reef system respectively. This scenario is similar to a hydraulic dam especially when the water level inside the lagoon becomes lower than the elevation of the crest of the reef flat. At this point, most of the entrapped water inside the lagoon would be concentrated and discharged through a reef gap. Moreover, when the tide changes into flood tide, the crest of the reef flat also has the function to be a barrier against flood tide when the water level is lower than the crest of the reef. Thus, the flood tide (onshore current) is also concentrated into the reef gap. The first and second peaks of 20-minute average velocity correspond to offshore current and onshore current respectively. Storm condition also forced and triggered the generation of wave height nearly 1.0m at the shoreline. Given this magnitude, it is expected that a much stronger offshore current will yield. However, for safety and precautionary reasons, the equipment had to be relocated to a less risky position which then measured the maximum velocity at 0.25m/s (Fig. 7b). Based on water level and current velocity data, an inverse proportionality relationship has been established as shown in Fig. 8. It is evident that the existence of high-speed current at the reef gap occurs during low tide condition. This scenario has been verified by Japan Coast Guard and local people as to the period when the drowning accidents occurred in Ishigakijima, Okinawa (Nishi et al. 2007).

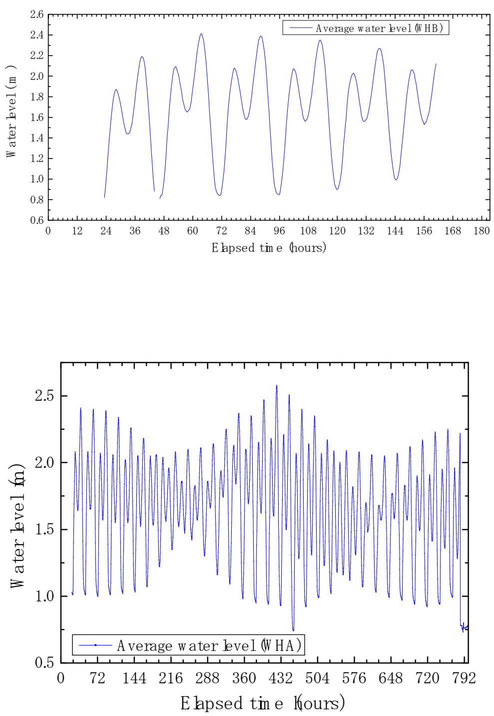

Figure 6. Tide record at the study site (upper panel) normal condition (June 25 – July 1, 2006), (lower panel) storm condition (July 1 – July 25, 2006)

Mean water level

Mean water levels inside and outside of coral reef produce spatial gradients which enhance the flow around a reef gap. To reveal the mechanism of strong offshore and onshore currents through a reef gap, four water level gages were installed on the hard sea bed. The installation points are shown in Fig. 9, one located outside the coral reef at the reef gap, another one on the reef flat near the reef edge, one in the middle of the lagoon, and one in front of the carbonate beach. The water level was measured every 1 second and expected to measure and run up to 11 days. However, due to some mechanical problems, data were stored for the first 36 hours during the first fieldwork. Superposition of four mean water level data is shown in Fig. 10.

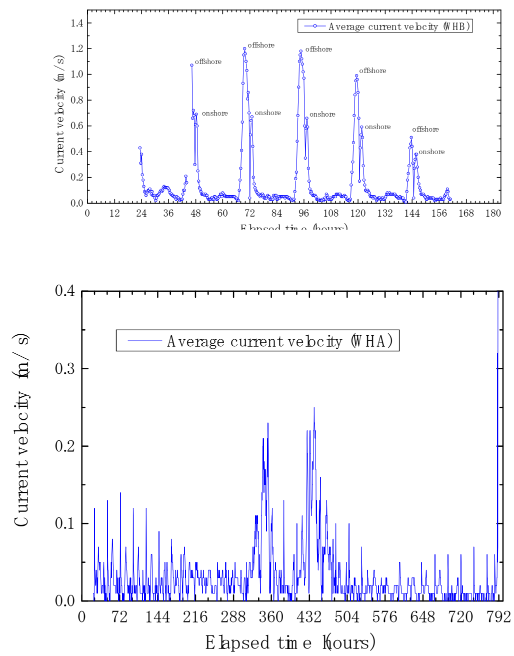

Figure 7. 20-minute mean velocity record (upper panel) normal condition (June 25 – July 1, 2006) (lower panel) storm condition (July 1 – July 25, 2006)

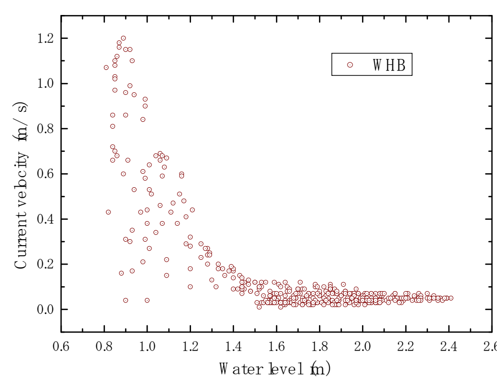

Figure 8. Relationship between current velocity and water level

Furthermore, it has been established that the spatial difference in mean water level is indeed significant especially during the lowest low tide. From the

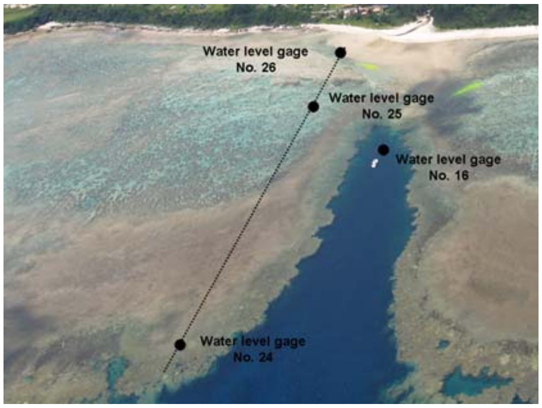

Figure 9. Orientation of water level gages (Gage 16 at the reef gap, Gage 26 on the carbonate beach, Gage 25 in the reef lagoon, and Gage 24 on the reef edge)

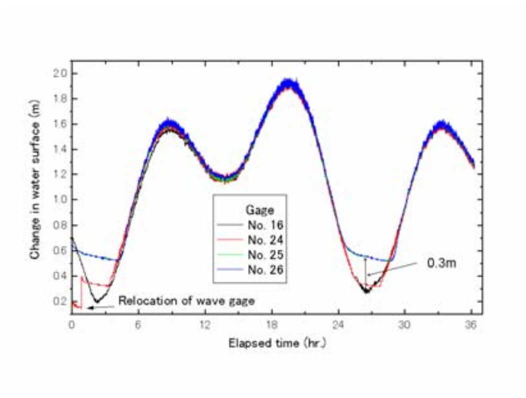

Figure 10. Mean water level outside of coral reef (No.16), on reef edge (No. 24), in the middle of lagoon (No.25), in front of carbonate beach (No.26)

field measurement, it was revealed that the mean water level inside a coral reef was higher than the mean water level outside of coral reef by as much as 0.3m (Fig. 10). Translating this gradient in terms of velocity expressed by $v = \sqrt{2gh}$, where g represents gravitational acceleration and h is the difference in water head, results into a rough estimation of 2.4m/s that is in fact twice as much as that from the observed data. This clearly shows that a spatial gradient of 0.3m would generate a strong current by more than 1m/s at the reef gap which is considered to be an upper limit of coastal users' (swimmers, etc) workability in water specifically in Japan.

Conclusion

The nearshore hydrodynamic study described the reef rip current phenomenon generated by tide and wave has revealed the following;

(1) During low tide conditions, the maximum 20-minute average velocity was measured as much as 1.2m/s even though the significant wave height is small (0.12m).

(2) The reef gap has a function to control exchange of water mass inside the coral reef especially during low tide. The reef flat works as a boundary to entrap the water in the lagoon and allows it to be discharged through the reef gap at low tide.

(3) A resultant spatial gradient in the mean water level inside and outside of coral reef is one of the most important mechanisms of the existence of a strong reef rip current.

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