Original Research

Importance of the Initial Waveform and Coastal Profile for Tsunami Transport of Boulders

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Abstract

The 2004 Indian Ocean tsunami transported large boulders shoreward at Pakarang Cape, Thailand. To elucidate boulder transport processes using their original locations, initial tsunami waveform, and coastal profiles, we conducted a cross-sectional calculation. Our results indicate that the tsunami (trough arrives first) might have displaced boulders and cast some on the tidal bench. However, if the wave crest arrives first, only some reef-edge boulders are displaced and emplaced on the tidal bench. More and larger boulders are displaced and deposited on the tidal bench when the reef slope is gentle, as at Pakarang Cape, than for a steep slope case.

Keywords: 2004 Indian Ocean tsunami, tsunami boulders, Pakarang Cape, numerical model

Introduction

Thousands of meter-long boulders of reef rocks are now scattered on the ca. 800-m-long tidal bench at Pakarang Cape, Thailand (Fig. 1a, [1]). No boulders were observed from a satellite image taken before the tsunami. Goto et al. [1] suggested that the 2004 Indian Ocean tsunami generated by the earthquake off Sumatra was directed eastward and struck the reef rocks and coral colonies, originally located on the sea bottom of less than 10 m depth. Subsequently, the tsunami transported the boulders shoreward. Abundant boulders, which were probably transported by the 2004 tsunami, are also visible at Hua Krang Nui Cape, approximately 10 km north of Pakarang Cape (Figs. 1a and 2).

The scene at these capes – displacement of such meter-long boulders by the tsunami has been observed only rarely – only a few boulders were reported at Phi Phi Don Island, Thailand [2], and northwestern parts of Sumatra Island, Indonesia [3]. Considering these facts, it remains to be clarified why spectacular boulder fields were formed only on the tidal bench of certain capes and some minor boulders at other limited areas. Kelletat et al. [2] described that the 2004 tsunami was not able to dislocate large boulders to a great degree based on their field observation in Thailand. However, a tsunami's boulder displacement capability is probably related not only to the shape and weight of boulders and the wave properties (height and period). It is also probably related to the coastal profiles and the original situation of boulders: their position, whether scattered or attached to the reef rock, and the waveform, whether a wave trough or crest arrives first. For example, the coastal profile at Pakarang Cape (Fig. 1a) is gentle compared to those of other reefs in Thailand, such as that of Phi Phi Don Island (Fig. 1b). Therefore, effects of these parameters on boulder displacement should be investigated.

To understand the relation among these parameters affecting boulder displacement, we conducted a cross-sectional numerical calculation using the Boulder Transport by Tsunami (BTT) model developed by Imamura et al. [4].

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Methods

Numerical Model for Tsunami Inundation

Cross-sectional calculation is suitable for evaluating effects of wave properties and the coastal profiles on boulder displacement by a tsunami because it is easy to change these parameters. Although cross-sectional calculation is inadequate to investigate boulder displacement when the tsunami behavior is complex because of the complex coastal profile, the coastal profile and behavior of the 2004 Indian Ocean tsunami at Pakarang Cape, especially the first run-up and backwash waves, were not complex [1]. This study specifically examines the effect of the original location of boulders, waveform, and coastal profiles on boulder displacement. It is not intended to yield a detailed reproduction of the boulder displacement process at Pakarang Cape. We therefore conducted a cross-sectional calculation of tsunami inundation and boulder displacement.

Shallow-water theory was used for numerical calculation of tsunami propagation in the shallow region and the run-up [5].

$$\frac{\partial \eta}{\partial t} + \frac{\partial M}{\partial x} = 0 \tag{2.1}$$

$$\frac{\partial M}{\partial t} + \frac{\partial}{\partial x}\left(\frac{M^2}{D}\right) + gD\frac{\partial \eta}{\partial x} + \frac{gn^2}{D^{7/3}}M|M| = 0 \tag{2.2}$$

In these equations, η denotes the vertical displacement of the water surface above the still water surface, M is the discharge flux in x direction, D represents total water depth ($= h + \eta$), and n is Manning's roughness coefficient. Manning's roughness coefficient was estimated as 0.025 for the sea bottom and on land. The staggered leap-frog method, which is a finite-difference method, was used to solve these equations numerically [5].

For analyses of boulder transport, we used a one-dimensional BTT-model [4]. External forces acting on the boulder, including those forces produced by the tsunami wave current, are represented as hydraulic force F_m, the frictional force at the bottom F_b, and the component of the gravitational force F_g along the slope [4].

$$\rho_s V \ddot{X} = F_m - F_b - F_g \tag{2-3}$$

Therein, ρ_s signifies boulder density, V is boulder volume, and X is boulder position in the x-direction. In addition, F_m represents the sum of the forces of drag and inertia [4].

$$F_m = C_D \frac{1}{2}\rho_f A(U - \dot{X})|U - \dot{X}| + C_M \rho_f V \dot{U} - (C_M - 1)\rho_f V \ddot{X} \tag{2-4}$$

In this equation, U is the current velocity at the position of the boulder, A is the projected area of the boulder against the current, and C_D and C_M are the respective coefficients of drag and mass. In addition, F_b and F_g are represented as in the following equations:

$$F_b = \mu(\rho_s - \rho_f)Vg\cos\theta \frac{\dot{X}}{|\dot{X}|} \tag{2-5}$$

$$F_g = (\rho_s - \rho_f)Vg\sin\theta \tag{2-6}$$

...where θ is the angle of the slope at the position of the boulder and μ is the coefficient of friction.

Imamura et al. [4] introduced an empirical variable coefficient of friction $\mu(t)$ by assuming that the coefficient decreases with decreased ground contact time when the block was transported by rolling or saltation.

$$\frac{\mu(t)}{\mu_0} = \frac{2.2}{\beta^2 + 2.2} \tag{2-7}$$

In this expression, μ_0 is the coefficient of dynamic friction during sliding and β is the degree of contact between the block and the floor. Using this parameter, the model is useful to explain various modes of transport − sliding, rolling, and saltation − and reproduces the experimental and field results well [4].

Initial Setting

The typical coastal profile at Pakarang Cape is used for this analysis (Figs. 1c and 1d); the length of the tidal bench is assumed to be 700 m. We generated a single incident wave (sine wave), which has a period of 30 min, from 100 km distance from the shoreline (Fig. 1c). Regarding the 2004 Indian Ocean tsunami, the wave trough arrived first at Thailand [6]. We input an incident wave with amplitude of -2.0 m to evaluate the effect of this (the wave trough propagates first, hereinafter "trough-start"; Fig. 1c). This incident wave period and amplitude resemble those offshore of Thailand. We also input an incident wave with amplitude of +2.0 m (the wave crest propagates first, hereinafter "crest-start") to investigate the difference of boulder displacement depending on the initial waveform. Each spatial grid cell is 10 m, and the calculation time is 7,000 s after tsunami generation.

The inclination of the reef slope at Pakarang Cape is considerably gentler (about 1/100) than the typical reef slope (e.g. 1/10-1/50) surrounding small islands such as Phi Phi Don Island (Fig. 1b) and the Mu Ko Similan Marine National Park, Thailand [7]. We modified the coastal profile at Pakarang Cape to have an inclination of the reef slope with 1/10 up to 40m depth to investigate the coastal profile effect (Fig. 1e). The bathymetries offshore of the reef slope, the tidal bench, and on land were set equal to those at Pakarang Cape. We input an incident wave with amplitude of -2.0 m and a period of 30 min for this case.

We used the maximum (4.1 × 2.5 × 2.2 m) and average size (1.8 × 1.3 × 1.1 m) boulders at Pakarang Cape for this analysis. These boulders' densities are assumed to be 1.62 g/cm^3. Goto et al. [1] estimated the original position of these boulders between the reef edge and water depth as shallower than 10 m. The original positions of boulders are uncertain within this range. Therefore, we set average and maximum boulders at 7 positions with 200 m intervals 100-1300 m offshore from the reef edge, which corresponds to the reef edge to approximately 10 m water depth (Fig. 1d). No interaction (e.g. collision or shielding effect) exists among these boulders.

Most boulders are rounded, ellipsoid to rectangular solid, without sharp broken edges. The absence of sharp broken edges suggests that these boulders were originally lying on the seabed (scattered or in clusters) in front of the reef edge already before the tsunami [1]. Therefore, we ignored the detachment process of boulders and set the boulders on the sea floor. Initial orientations of boulders are unknown. However, Imamura et al. [4] revealed, based on the hydraulic experiment, that the boulders are moved mainly with the long axis perpendicular to the current direction

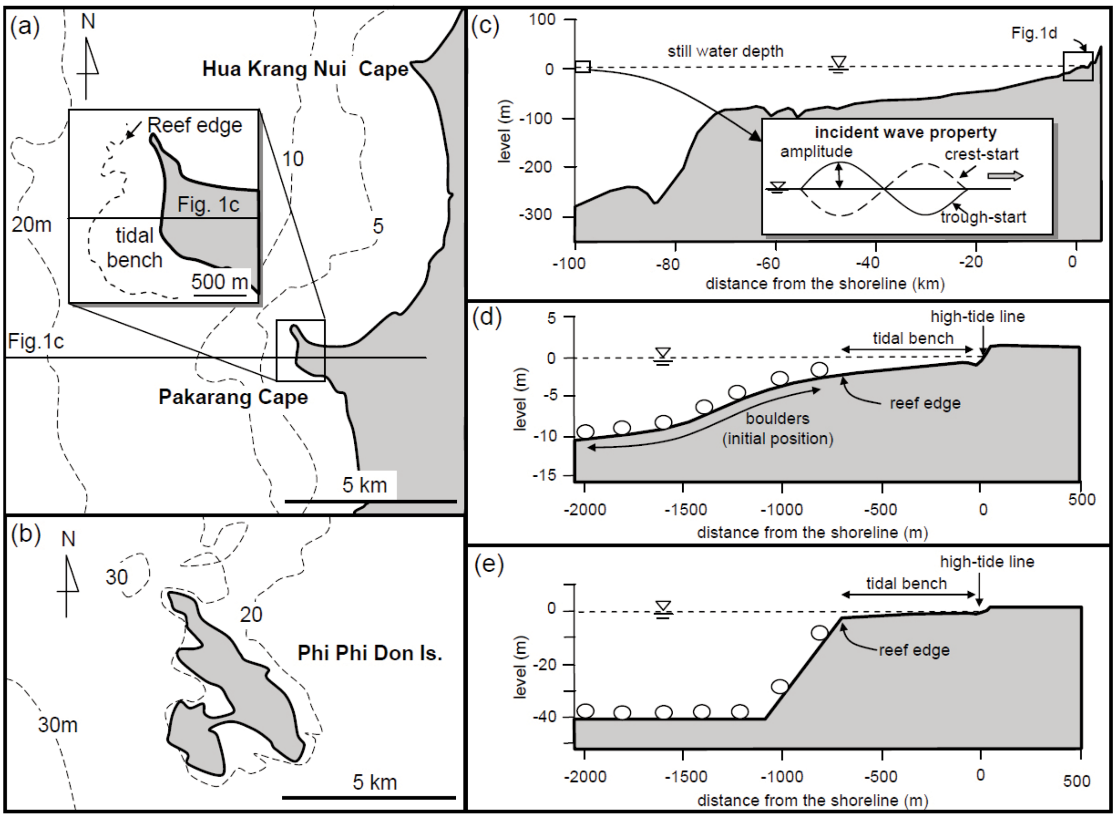

Fig. 1. (a) Location map of the studied area at Pakarang Cape, Thailand. (b) Bathymetry around Phi Phi Don Island, Thailand. Its difference from the bathymetry from that of Pakarang Cape is noteworthy. (c) Schematic diagram of the coastal profile and incident wave used for this study. (d) Schematic diagram of the coastal profile near Pakarang Cape. Original positions of boulders are also shown. (e) Schematic diagram of the coastal profile that was modified to be a reef slope inclination of 1/10.

Fig. 2. An oblique west-facing aerial photograph of the Hua Krang Nui Cape showing the boulders' distribution.

despite the boulder's original orientation. Moreover, original orientations of boulders do not affect the total distance that the boulders are displaced when the ratio between the long and short axis is less than 2:1 [4]. Therefore, we assumed that long axes of the boulders are perpendicular to the current direction and determined the projected area *A* in equation (2.4).

Numerical Results for Tsunami Inundation and Boulder Transport Processes

Trough-Start Wave (the 2004 Indian Ocean Tsunami Case)

Immediately before the arrival of the first wave crest, the tidal level decreases approximately 6.6 m: the tidal bench was largely exposed above the tidal level (Figs. 3a and 3b). When it reached the reef edge, the height of the first crest of the wave from the still water depth was estimated as 2.7 m. Consequently, the wave height (double wave amplitude) becomes approximately 9.3 m around the reef edge. Then, the first crest of the wave reached the shore and inundated the land (Figs. 3c and 3d). The maximum wave height at the shoreline during the calculation time was calculated as 6.0 m and decreased to 5.1 m at 500 m inland from the shoreline (Fig. 4a). This value is approximately consistent with the observed values at the coastal area of Pakarang Cape (from 7 m to 4 m height landward [1, 8]).

The fastest current velocity of the tsunami in the studied region (9.0 m/s) was generated at approximately 1400 m from the high-tide line (700 m offshore from the reef edge) (Fig. 4a) because the wave height becomes the highest at that point as a result of the receding tidal level immediately before the arrival of the first wave crest. The maximum current velocity on the tidal bench is estimated as 7.4-7.5 m/s: it suddenly decreases at the high-tide line to be 5.3 m/s because of the presence of the steep slope at the beach.

Figs. 5a and 5b respectively show time-series variations of the average and maximum boulder positions. As these figures show, the boulders' total displacement distances are highly variable, depending on the original position. The average and maximum boulders furthest offshore (1300 m offshore from the reef edge) respectively move approximately 1360 and 550 m shoreward; the boulders in front of the reef edge respectively move approximately 770 and 610 m. All average boulders were deposited on the tidal bench, but no boulders reached land. The maximum boulder approximately reached its present position (60 m offshore from the high-tide line) when we assume that it was originally located 100 m offshore of the reef edge (Fig. 5b). The backwash wave current re-displaced several average and maximum boulders less than 70 m seaward (Figs. 5a and 5b).

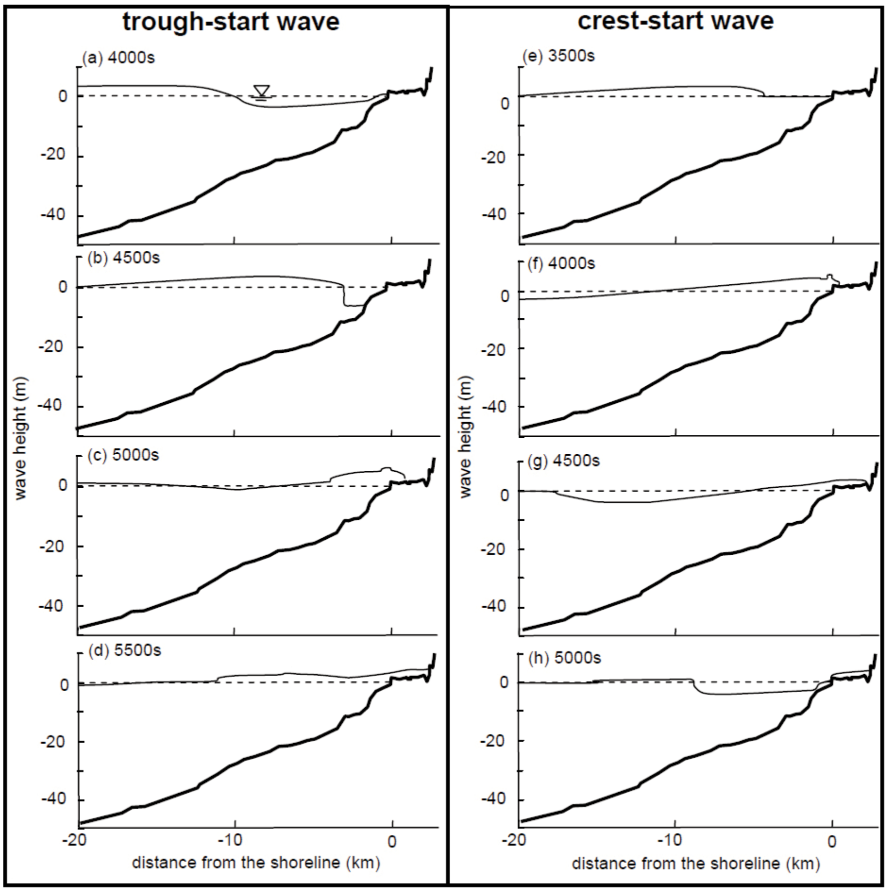

Fig. 3. (a)-(d) Snapshots of computing inundation pattern of the trough-start wave at 4000-5500 s after tsunami generation, and (e)-(h) of the crest-start wave at 3500-5000 s after the tsunami generation. Dotted and solid lines respectively mark the still water depth and tsunami wave.

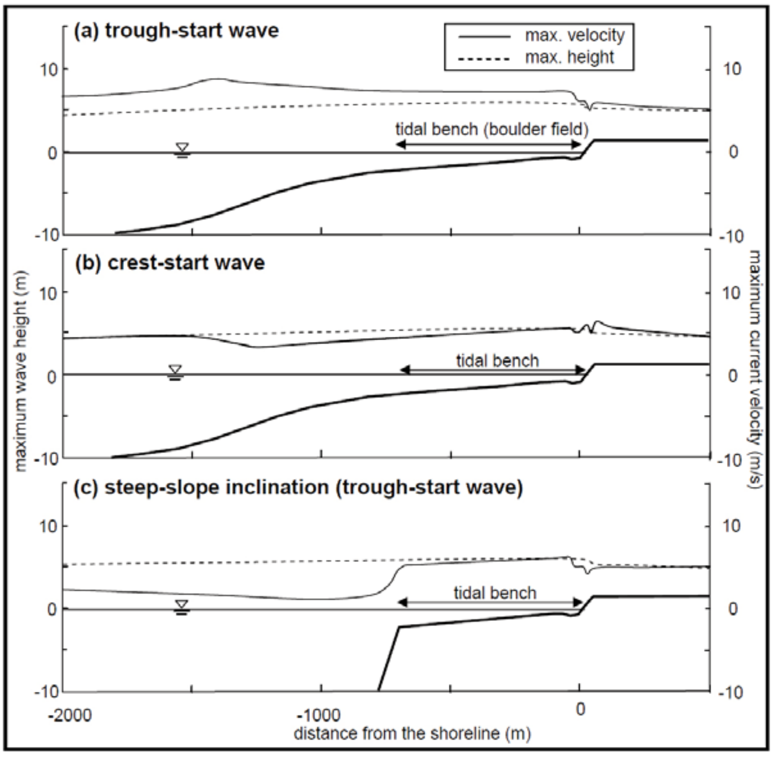

Fig. 4. Numerical results of the maximum current velocity (solid line) and wave height (dotted line) during the calculation time for (1) a trough-start wave, (2) a crest-start wave, (3) and a trough-start wave with slope inclination of 1/10.

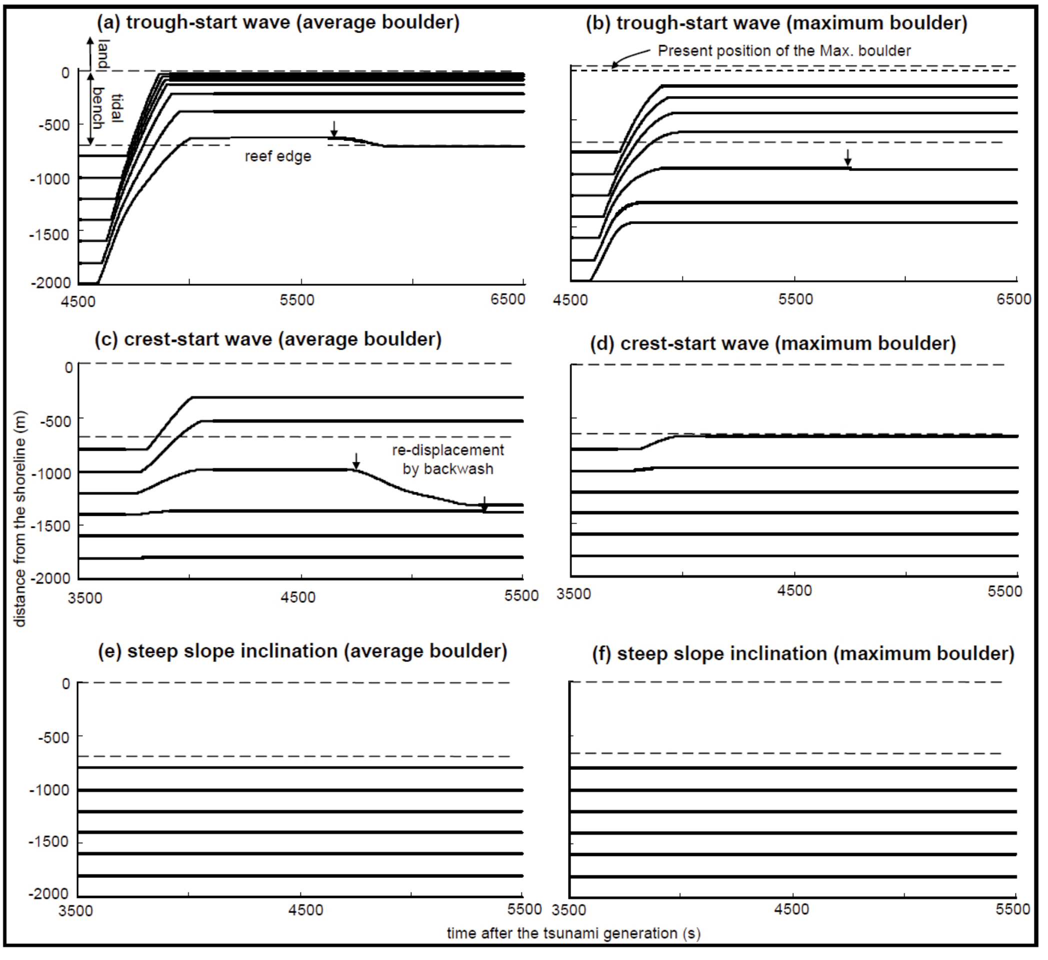

Fig. 5. Time series variation of the positions of (a) average and (b) maximum boulders by the trough-start wave, (c) average and (d) maximum boulders by the crest-start wave, and (e) average and (f) maximum boulders by the trough-start wave with a slope inclination of 1/10. Arrows indicate the onset of the movement of boulders seaward by backwash.

Crest-Start Wave

We also conducted a calculation for crest-start wave propagation to investigate the difference between the effect of the trough-start and crest-start waves. The wave crest height measured from the still water depth is approximately 3.0 m around the reef edge (Fig. 3e). This height is of a similar range to that of the trough-start wave. Then, the first crest of the wave inundated the land (Figs. 3f-3h). The tidal level did not recede before the arrival of the wave's first crest. Therefore, the wave height offshore of the reef edge becomes considerably smaller than the case of the trough-start wave. Consequently, the maximum current velocity of the tsunami offshore of the reef edge is small (3.3-4.5 m/s). In contrast, the maximum wave height and the current velocity at the shoreline are estimated as approximately 5.5 m and 6.3 m/s, respectively, whose values are almost identical to those of the trough-start wave.

Because of the low current velocity offshore of the reef edge, the displacement distances of boulders by the crest-start wave were considerably shorter than those by the trough-start wave (Figs. 5c and 5d). The average boulder 100 m offshore from the reef edge moved approximately 490 m, although the boulder at the furthest offshore did not move (Fig. 5c). The maximum boulder at 100-300 m offshore from the reef edge were displaced 130-30 m shoreward (Fig. 5d). In contrast, boulders at 500-1300 m offshore from the reef edge were not displaced. The average boulder at 500 m offshore of the reef edge was displaced approximately 220 m shoreward by the run-up wave; it was re-displaced approximately 330 m seaward by backwash, and stopped further offshore from its initial position because the boulder was displaced by the run-up wave and stopped on the slope. At this position, gravity moved the boulder down the slope during the backwash process.

Steep Slope Inclination (Trough-Start Wave)

For steep slope inclination, the maximum current velocity offshore of the reef edge was considerably small (Fig. 4c) because the water depth suddenly increased offshore of the reef edge and the wave height offshore of the reef edge is still low. The point with the fastest maximum current velocity generated was observed around the reef edge (Fig. 4c). The current velocity distribution offshore of the reef edge differs considerably between gentle and steep slopes. On the other hand, the maximum wave height and the current velocity at the high-tide line are estimated as 6.1 m and 5.1 m/s, respectively (Fig. 4c), which are almost identical to those of the trough-start wave at the gentle coastal profile of Pakarang Cape (Fig. 4a).

Because of the markedly low current velocity of the tsunami offshore of the reef edge and the presence of a steep slope, no boulders reached the tidal bench in this case (Figs. 5e and 5f).

Discussion

Our results show that both average and maximum boulders at Pakarang Cape might have been displaced from their original positions by the 2004 Indian Ocean tsunami (Figs. 5a and 5b). Moreover, depending on their original positions, they are calculated as being deposited on the tidal bench. Especially, all average boulders reached the tidal bench and were deposited on it. Moreover, when we set the maximum boulder at the reef edge, it reached close to its present position. These results suggest that our numerical results explain the present distribution of boulders at Pakarang Cape. It is noteworthy, however, that our cross-sectional analysis did not incorporate the effects of the subsequent waves, precise wave properties (period, height, and form), and local effects of bathymetry, which are difficult to include in the cross-sectional calculation. Although this study simulated the bathymetry and tsunami wave properties around Pakarang Cape, the displacement process and the final resting positions of the boulders should be investigated based on better-detailed future calculations.

Compared to the trough-start wave, the crest-start wave has much less energy to displace the boulders on the offshore sea bottom even though the initial wave amplitude and period are the same (Figs. 5c and 5d). This difference

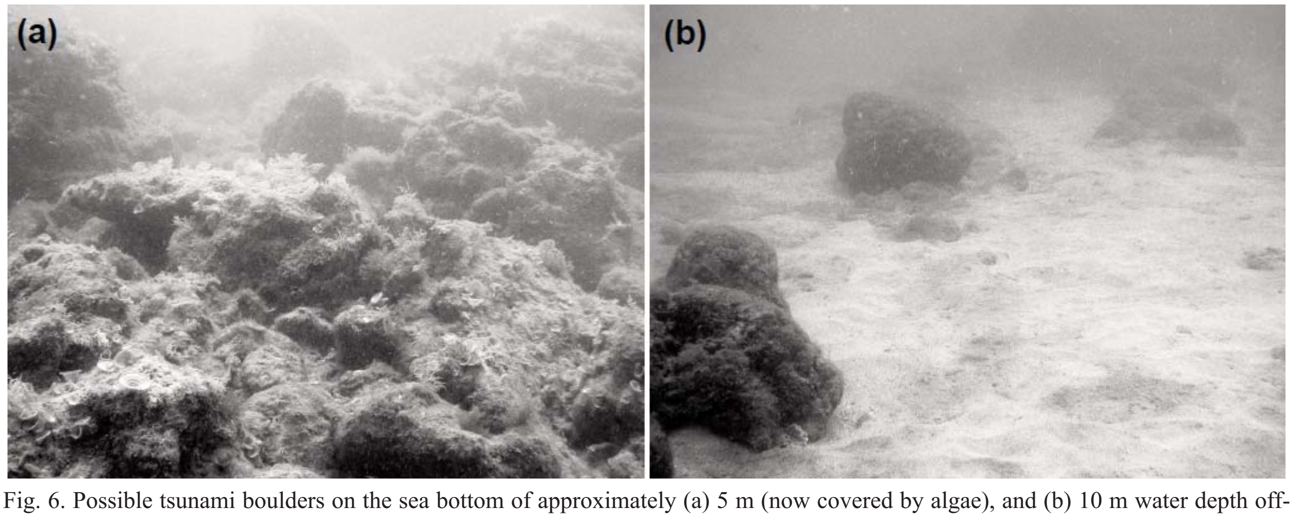

Fig. 6. Possible tsunami boulders on the sea bottom of approximately (a) 5 m (now covered by algae), and (b) 10 m water depth offshore of Pakarang Cape. Courtesy: S. A. Chavanich.

is attributable to the difference of the current velocities offshore of the reef edge (Figs. 4a and 4b). The current velocity of the trough-start wave at 700 m from the reef edge reaches 9.0 m/s, whereas that of the crest-start wave is <4.5 m/s. This difference results from the difference of the wave height of the tsunami around the reef edge. The tidal level receded before the arrival of the first crest of the trough-start wave, although the tidal level does not recede in the case of the crest-start wave. Therefore, the trough-start wave height (double wave amplitude) at the offshore of the reef edge becomes very large. Consequently, the boulders were displaced with longer distance and larger number by the trough-start wave (Figs. 5a and 5b) than in the case of the crest-start wave (Figs. 5c and 5d).

When the inclination of the reef slope was steep (1/10), the boulders rarely displaced, even though we input the trough-start wave. This is because the high current velocity that is capable of displacing boulders was generated only from around the reef edge to the tidal bench. Moreover, the hydraulic force of the tsunami was insufficient to overcome the boulders' resisting forces attributable to gravity. These results suggest that the coastal profile is also an important factor determining whether boulders were deposited on the tidal bench and on land.

The wave heights and current velocities at the shoreline of each case were almost identical (Fig. 4). Nevertheless, the distributions of the maximum current velocities offshore of the reef edge differed considerably, suggesting that the degree of damage caused by the tsunami on land does not necessarily correspond to the level of damage on the shallow sea bottom. Consequently, the tsunami wave height and inundation area measured on land behind a reef are not necessarily useful for evaluating boulder displacement or damage to the shallow sea bottom, such as that to coral and marine ecosystems.

Implications for Tsunami Boulders Displaced by the 2004 Indian Ocean Tsunami

The tsunami wave heights around Pakarang and Hua Krang Nui Capes are estimated as less than 7 m and the tsunami inundated ca. 2.5 km inland [1, 8, 9]. This wave height is not considerably high among the tsunami-damaged area in the Indian Ocean countries. Nevertheless, thousands of meter-long boulders of reef rocks are now scattered on the tidal benches of these capes. As described above, the wave height and inundation area estimated on land are not necessarily useful for discussing boulder displacement. Several factors might have affected the formation of the spectacular tsunami boulder fields at these capes.

Importance of Boulder Sources

No boulders are displaced if no source rocks or boulders are distributed in the tsunami path. Moreover, the presence of a boulder source offshore of a reef edge that is already broken and scattered before the tsunami is important for determining whether many tsunami boulders are observed on the tidal bench or on land. Goto et al. [1] suggested that the Pakarang Cape boulders were originally lying on the seabed (scattered or in clusters) in front of the reef edge before the tsunami, based on their lack of sharp broken edges. Boulders of reef rocks on the shallow sea bottom are moved more easily by the tsunami than in the case in which the tsunami detaches boulders from reef rock. For example, Noormets et al. [10] estimated that a boulder deposited on the North Shore of Oahu, Hawaii, was located originally on the edge of the shore platform, and that it was detached and emplaced on the platform by a swell wave or tsunami, thereby transporting it further inland. They estimated that more than 60-70% fracture is necessary to detach the boulder from the shore platform edge by a swell wave or tsunami. The hydraulic force of the tsunami is expected to be weakened during the boulder detachment. Therefore, if the boulders were not originally lying on the seabed in front of the reef edge before the tsunami, only small boulders would be displaced by the tsunami, and only for short distances.

The displacement of living coral colonies might have been rather complex because some were attached to solid substrates. In fact, Campbell et al. [11] reported that coral attached to solid substrates was largely unaffected, although coral growing in unconsolidated substrates suffered much greater damage. Moreover, they described that the type of damage observed was influenced strongly by which coral was present at a particular site or depth [11]. Living coral colonies' adherence to the bottom should be estimated and included in the numerical model to evaluate their displacement.

Possible Unrecognized Boulders Deposited under the Sea

We have recognized the boulders that were deposited on the tidal bench or on land because they are visible and readily identifiable. Even boulders displaced by the tsunami are difficult to recognize as such if they are deposited under the sea. According to our underwater survey offshore of Pakarang Cape, meter-long boulders of reef rocks were also scattered at 4-5 m water depth (Fig. 6a), and their concentration decreases toward the deeper zone (ca. 10 m) (Fig. 6b). These boulders were likely to have been displaced by the 2004 Indian Ocean tsunami and deposited at their present positions because little coral is accreted on these boulders; separate coral formations are only approximately 4-5 cm diameter, which suggests that live coral was recently recruited in the area, possibly after the 2004 Indian Ocean tsunami [1]. Moreover, our numerical results further support this idea that meter-long boulders in these water depths were easily displaced by the 2004 tsunami (Figs. 5a and 5b). Therefore, many tsunami boulders might have been distributed offshore of the reef edge around Pakarang Cape.

Although tsunami boulders were reported from only several regions, many unrecognized boulders might have been displaced by the 2004 Indian Ocean tsunami on the shallow sea bottom of tsunami-affected countries. In fact, an underwater survey at the Surin Islands Marine National Park, Thailand immediately after the tsunami event found that many large reef rocks and coral colonies were concentrated around the bottom of the slope (S. A. Chavanich, personal communication). Identification of such underwater tsunami boulders is, however, extremely difficult through emergency tsunami or geological surveys.

First Arrival of the Trough-Start or Crest-Start Waves

Keating et al. [12] and Kench et al. [13] reported that the largest fragments transported on land by the tsunami were a few tens of centimeters at the Maldives, which is much smaller than in the Thailand case, where a 4-m long boulder was transported onto the tidal bench by the tsunami. One important factor is the mutual difference of the tsunami wave heights in the Maldives and Thailand: waves of the latter were several times larger than those of the former. Moreover, we infer that the first arrival of the trough-start or crest-start waves might have been an important factor. Regarding the 2004 Indian Ocean tsunami, the wave trough arrived first at Thailand [6]. In this case, it is expected that the tidal level receded before the arrival of the wave's first crest. Consequently, the wave height (double wave amplitude) of the tsunami offshore becomes considerably higher than that of the trough-start wave (Figs. 4a and 4b). The arrival of the trough-start wave at the Thailand coast might also have affected the formation of the tsunami boulder fields there.

Coastal Profile Effects

The reef slope inclination is considerably more gentle at Pakarang Cape (Fig. 1a) compared to those of other reefs in Thailand. Our numerical results show that the reef slope inclination played an important role in boulder displacement by the tsunami. A tsunami on a gentle slope is capable of transporting numerous huge boulders over long distances (Figs. 5a and 5b), although, given the same magnitude of tsunami, it is unlikely that so many boulders would be displaced in the case of a steep slope (Figs. 5e and 5f).

This observation is also applicable for coral damage evaluation. Few studies have examined coral damage from the 2004 Indian Ocean tsunami in relation to coastal profiles, although Chavanich et al. [7] reported such data for the Mu Ko Similan Marine National Park in Thailand. Their field observations revealed that more severe coral damage occurred where the reef slope dropped gradually away from the shoreline at the park [7]. Our numerical results show that a higher current velocity is generated at a gentler slope than at a steep slope (Fig. 5). For that reason, a stronger and longer tsunami effect is expected at a gentle slope, which supports the observations of Chavanich et al. [7].

At Pakarang Cape, no source of boulders exists on the tidal bench because no back reef moat exists. However, if a coral reef has a moat with abundant coral colonies that can be the source of tsunami boulders, effects of the tsunami on coral colonies in the moat must be evaluated. The movement of coral colonies in the moat, however, depends largely on the coastal profiles (including the moat depth) as well as the distribution of coral colonies, adherence of coral to the bottom, and tsunami wave properties. Consequently, each case demands specific numerical calculation.

Conclusions

For this study, we used a one-dimensional BTT-model to investigate boulder displacement at Pakarang Cape by a tsunami. The initial waveform (trough-start or crest-start), the original setting of boulders (attached to the reef rock or scattered), and coastal profiles (steep or gentle) are important factors determining whether many boulders were displaced by the tsunami and deposited on the tidal bench or on land. We concluded that the following factors affected formation of the tsunami boulder field at Pakarang Cape:

1. abundant sources of boulders scattered or in clusters in front of the reef edge before the tsunami,
2. gentle reef slope inclination, and
3. arrival of the wave trough first at the cape.

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