PAGEOPH, Vol. 144, No. 3/4 (1995) 0033-4553/95/040555-14$1.50 + 0.20/0

Numerical Simulation of the 1992 Flores Tsunami: Interpretation of Tsunami Phenomena in Northeastern Flores Island and Damage at Babi Island

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Abstract—Numerical analysis of the 1992 Flores Island, Indonesia earthquake tsunami is carried out with the composite fault model consisting of two different slip values. Computed results show good agreement with the measured runup heights in the northeastern part of Flores Island, except for those in the southern shore of Hading Bay and at Riangkroko. The landslides in the southern part of Hading Bay could generate local tsunamis of more than 10 m. The circular-arc slip model proposed in this study for wave generation due to landslides shows better results than the subsidence model, It is, however, difficult to reproduce the tsunami runup height of 26.2 m at Riangkroko, which was extraordinarily high compared to other places. The wave propagation process on a sea bottom with a steep slope, as well as landslides, may be the cause of the amplification of tsunami at Riangkroko. The simulation model demonstrates that the reflected wave along the northeastern shore of Flores Island, accompanying a high hydraulic pressure, could be the main cause of severe damage in the southern coast of Babi Island.

Key words: The 1992 Flores earthquake tsunami, numerical simulation, landslide, hydraulic pressure, tsunami damage.

1. *Introduction*

On 12 December 1992, an earthquake of 7.5 M_s and an accompanying destructive tsunami struck the northeastern coast of Flores Island (Figure 1). There were 1,713 casualties and 2,126 people were injured. Half of these were due to tsunami (TSUJI *et al.*, 1993). An extremely large tsunami runup height of 26.2 m was measured at Riangkroko, in the northeastern peninsula of Flores Island. There are only two other examples in this century—the 1993 Sanriku earthquake tsunami and the 1993 Hokkaido Nansei-Oki earthquake tsunami—in which more than 20 m tsunami runup heights were observed.

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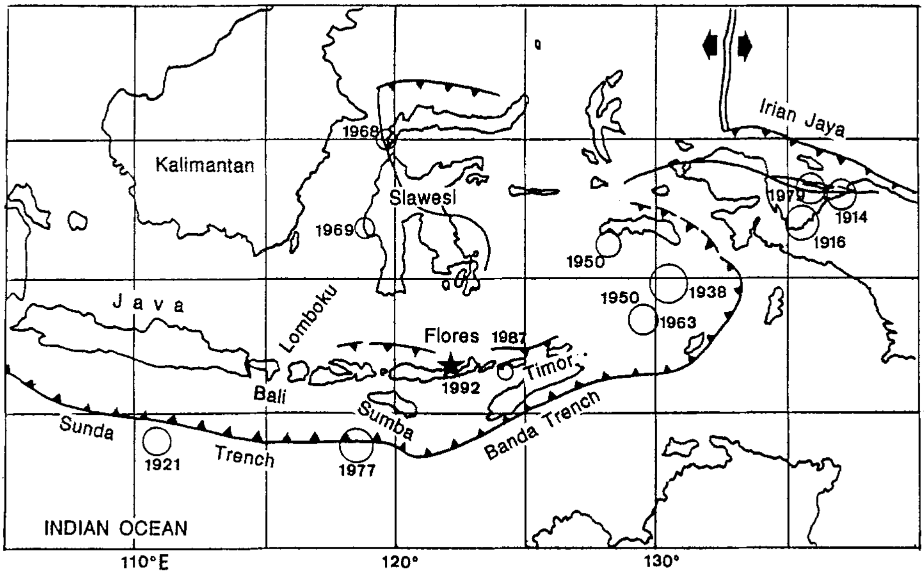

Figure 1
Map of the tectonics and epicenter of the earthquakes in eastern Indonesia. Flores Island is located in the back arc of eastern Sunda and western Banda thrusts.

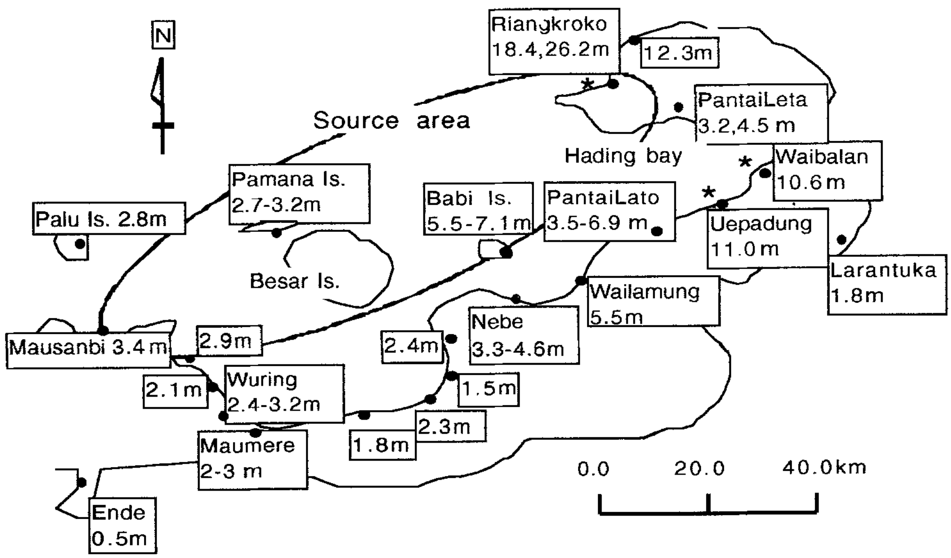

Figure 2
Measured tsunami runup heights in meters on eastern Flores Island and the tsunami source (TSUJI et al., 1993). A general trend of increasing runup height from west to east in this region is significant. The asterisks indicate the location of the landslide in Hading Bay.

An International Tsunami Survey Team (ITST) consisting of engineers and scientists from Indonesia, Japan, and the U.K., Korea and the U.S. conducted a field survey along the northeastern coast of Flores Island and several smaller offshore islands. Tsunami runup heights were measured as shown in Figure 2 and problems relative to the damage and the generation mechanism were pointed out. In this paper two problems associated with the 1992 Flores tsunami are investigated, because of their important role in preventing tsunami disasters in the future. The first problem concerns the mechanism which generated a giant tsunami with runup heights at Riangkroko, Uepadung, and Waibalan in Hading Bay of 10.6–26.2 m, which are much larger than those on the western part of Flores Island (Figure 2). The second point of concern is to investigate an underlying cause of the damage at Babi Island, where two villages located along the southern coast of Babi Island were completely destroyed due to a large wave force, even though the source lay to the north.

2. *Tsunami Source Model*

Our initial tsunami model uses one fault model based upon the quick Harvard CMT solution [event file M121292Y]. Taking into account the tectonics in this region (thrust in a back arc, HAMILTON, 1988), a shallow dip thrust fault as the source with (strike, dip, slip) = (61°, 32°, 64°) shown in Table 1, is selected from two mechanism solutions. According to the distribution of the aftershocks determined by the United State Geological Survey (USGS), the fault plane is approximately 100 km long and 50 km wide. An average dislocation of 3.2 m can be determined by using a rigidity of 4.0×10^{11} dyne/cm^2.

A numerical simulation of tsunami generation and propagation, the TUNAMI-N1 code (SHUTO *et al.*, 1990; IMAMURA *et al.*, 1993a), was carried out using one fault model. The lack of detailed topographical data in shallow regions and on the land made it very difficult to carry out runup simulations. The computed maximum water level along the coastline modeled as a vertical wall is associated with the computed runup height. Both are correlated as long as the slope of the shoreline is steeper than around 0.01 in this case. Therefore, in this model, the

Table 1

Fault parameter of the 1992 *Flores earthquake*

	M_0 ($\times 10^{27}$ dyn-cm)	Depth (km)	Strike (deg)	Dip (deg)	Slip (deg)	Length (km)	Width (km)	Dislocation (m)
East fault	4.8	3	61	32	64	50	25	9.6
West fault	1.6	3	61	32	64	50	25	3.2

Table 2

Computational condition

Governing equation	Shallow water theory (nonlinear theory)
Spatial grid size	300 m
Time step	1 sec
B.C. of coastal line	Perfect reflection condition (vertical wall)
Reproduction time	1 hour

computed maximum levels along the coastline are directly compared with the measured runup heights. The computational condition is summarized in Table 2. In Figure 2, the computed results are smaller than the measured runup heights in the eastern part of Flores Island, suggesting that the slip value on the eastern side of the fault might have been larger than that on the western side. Aftei several trials, a composite fault model with different siip values; 3.2 m in the west and 9.6 m in the east, was proposed (IMAMURA and KIKUCHI, 1994). In this model, the seismic moment of 6.4×10^{27} dyne-cm is kept and both segments have the same fault area of 50 km long and 25 km wide (Figure 3). The crustal movements estimated by the composite fault model with a depth of 3 km coincide with the crustal deformation measured by TSUJI *et al.* (1993). The computed maximum water levels using this model are compared to the measured runup heights in Figure 4. The numerical model with the composite fault model reproduces the distribution of the measured tsunami runup heights along the northeastern coastline of Flores Island, except for the southern shore of Hading Bay and Riangkroko.

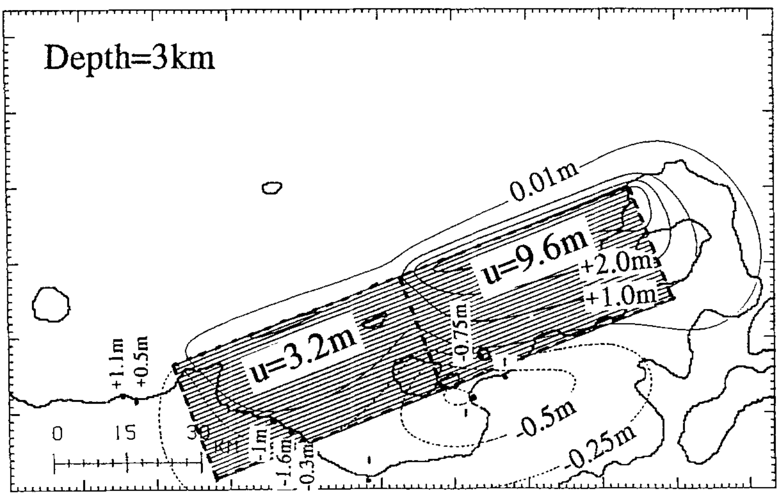

Figure 3
Composite fault model (IMAMURA and KIKUCHI, 1994) and its vertical displacement of ground. Moment release in the eastern part is larger than that in the western part.

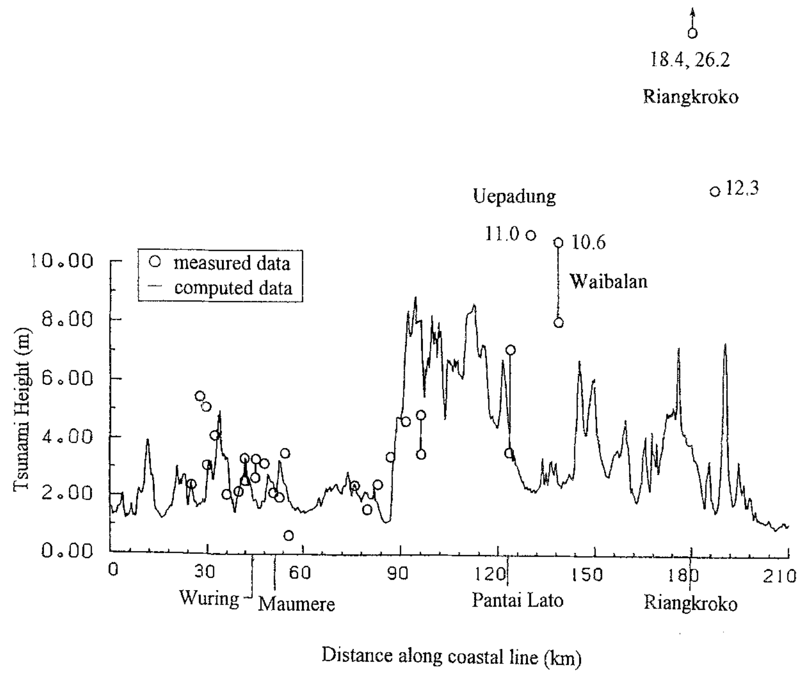

Figure 4
Comparison between the measured runup heights and the computed maximum water level along the northeastern coast of Flores Island.

3. *Tsunami in Hading Bay and Riangkroko*

Landslide in Hading Bay

As shown in Figure 4, the measured runup heights of 10.6 m at Waibalan and 7.6–11.0 m at Uepadung on the southern shore of Hading Bay, were considerably higher than elsewhere in this bay such as Pantai Lato and Pantai Leta. It is possible that abnormal runup heights were generated by other geological agents. ITST noticed large landslides along the southern shore of Hading Bay (YEH *et al.*, 1993), and reported that the landslide shear planes are almost vertical. Their planes form a steep and vertical cliff along the present shoreline approximately 150 m wide and 2 km long (Photo 1). The observed large runup heights are limited to the area of subaqueous slumps, suggesting the possibility that they were caused by landslide-generated waves rather than tectonic tsunami waves. A model which includes wave generation due to landslides may be required to reproduce the measured tsunami heights in the Flores tsunami event.

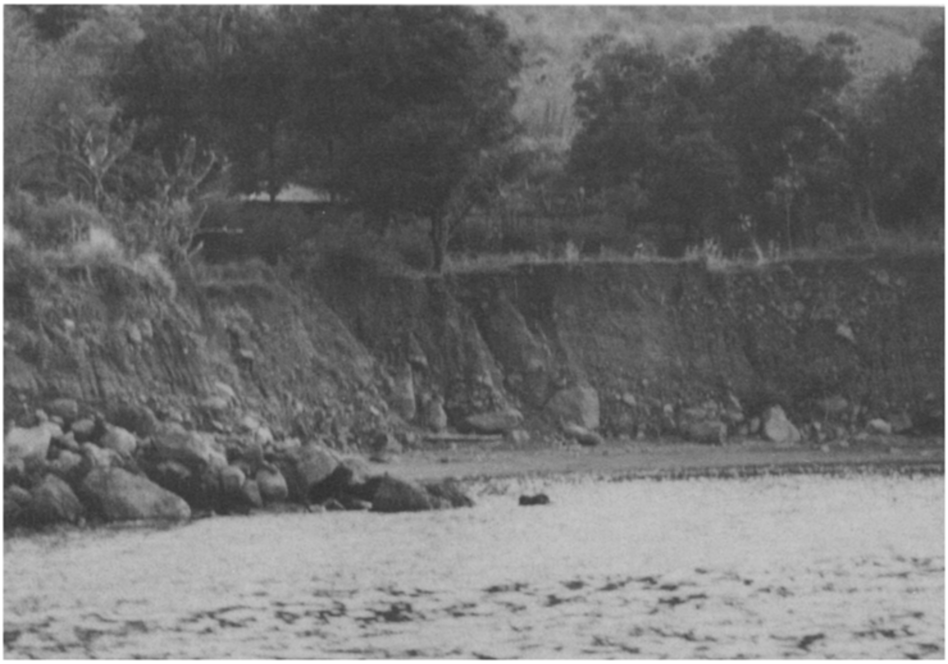

Photo 1
Landslide in Waibalan taken by the second field survey team in 1994. The cliff is 150 m wide and 2 km long. The average height of the cliff is around 10 m.

Wave Generation Model due to Landslides

There are several models for wave generation due to landslides. They range from the inflow volume method and unit-width discharge method (MING and WANG, 1993), to two-dimensional boxes model dropped vertically at the end of a semi-infinite channel (NODA, 1970). None of these methods can be applied directly to the present case, because higher tsunami heights were observed, not on the opposite side of the landslide area, but along the landslide and its surrounding area. In addition, the observed runup was higher than the level of the top of the landslide. In the present study, the subsidence model and the circular-arc slip model (see Figure 5) are proposed, since the cavity formed by subsidence could generate a wave propagating toward the coast (GICA, 1994). For wave generation due to landslides, modeling with runup condition is used. The averaged depth of 20 m and land height of 8 m are estimated from the field survey, while the radius of circular-arc slip of 30 m, and properties of the soil are assumed because no data pertinent to them are available. Assuming the same maximum vertical displacement in both models, the computed results demonstrate that the wave runup height (3.9 m) of the subsidence model is half that of the circular-arc slip model (8.2 m).

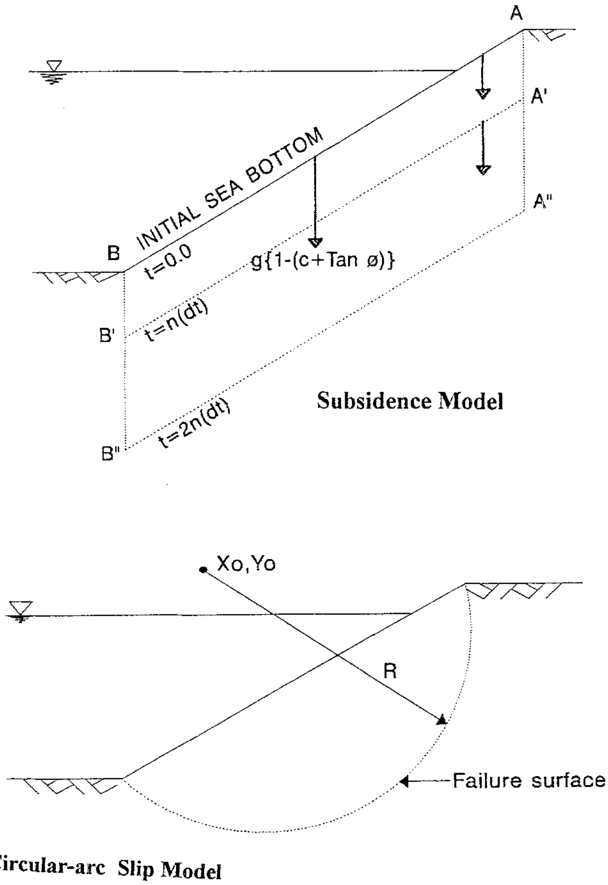

Figure 5
Subsidence (upper) and circular-arc slip (lower) models for the wave generation due to landslides. The deformation of sea bottom is calculated at every step based upon two models. c: soil cohesion, ϕ; soil friction angle, g; gravitational acceleration.

This is the reason that a deformation of the sea bottom near the toe of the landslide mass in the circular-arc slip, increasing the disturbances of the water surface, causes a wave propagation with a larger amplitude toward the coastal line. The maximum runup height of the circular-arc slip model is observed as identical to the ground level. The above results suggest that the circular-arc slip model more suitably reproduces the tsunami of more than 10 m observed in Flores. Unfortunately, the lack of field data such as landslide scale under the sea and soil properties does not allow us to compare the computed values with those measured in Hading Bay.

Riangkroko

An extremely large tsunami runup was measured in the small village of Riangkroko (Figure 6), where 137 people from a population of 406 prior to the

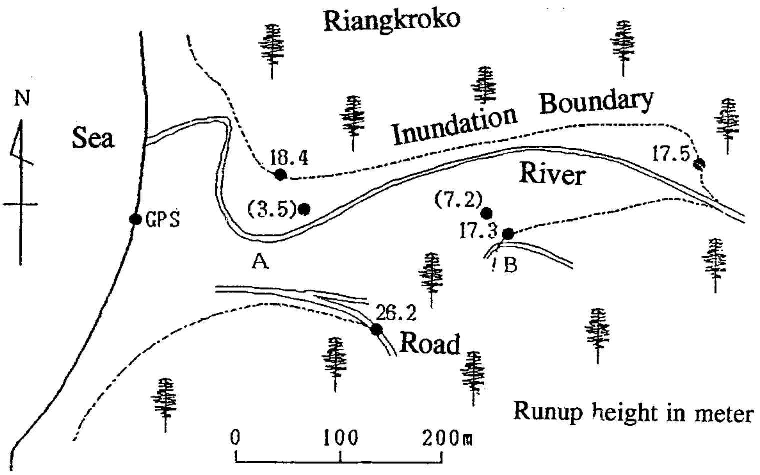

Figure 6
Inundation area and tsunami runup at Riangkroko. A maximum tsunami height of 26.2 m was measured. All houses were completely washed away by the tsunami. Numerals in parenthesis are the inundated tsunami heights.

event lost their lives. The village is located at the mouth of a small river, the Nipar River, with its northwestern side facing the Flores Sea. A remarkably steep sea bottom existed offshore of the village (Figure 7), similar to the case of Okushiri Island in the Hokkaido Nansei-Oki earthquake tsunami of 1993. The maximum

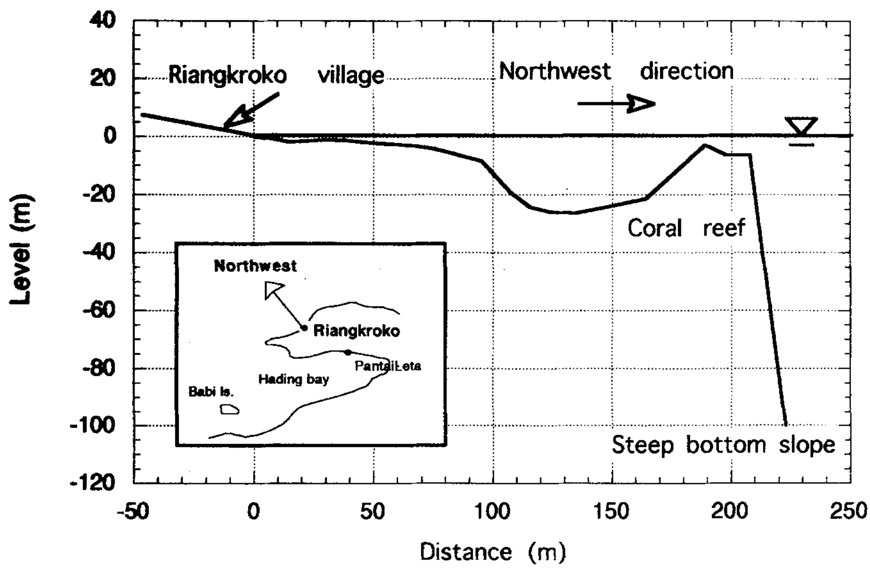

Figure 7
Topography of sea bottom offshore Riangkroko. A steep bottom slope after passing the coral reef is significant, suggesting large amplification on the slope and energy trapping on the coral reef in the shallow region.

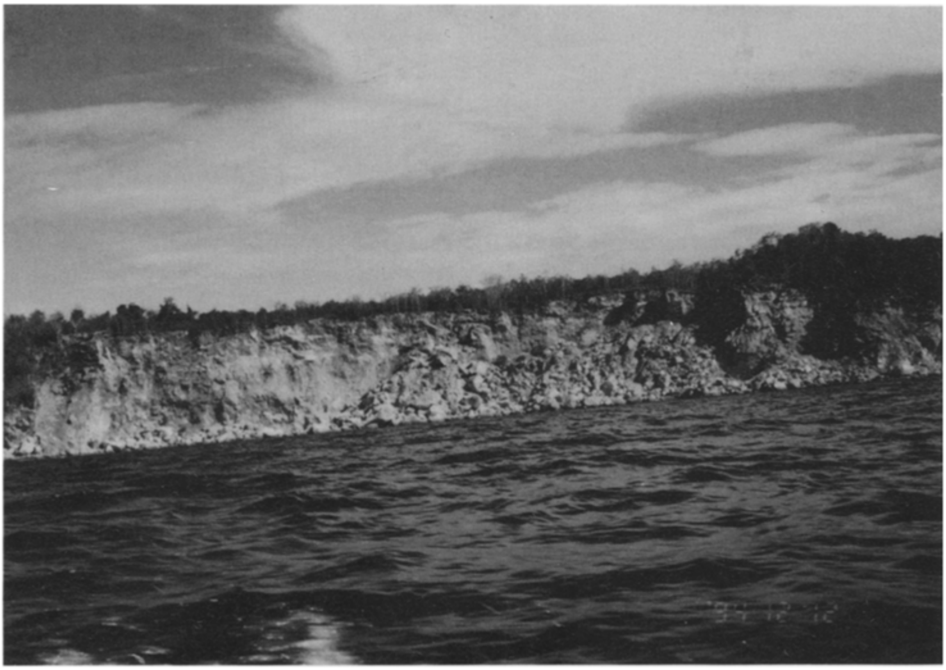

Photo 2
Huge landslide nearby Riangkroko taken by the second field survey team in 1994. Its height was estimated to be more than 30 m.

runup height measured at Riangkroko was 26 m and the average of heights based on four different tsunami marks was 19.6 m. This indicates that the magnitude of the tsunami runup is probably not an isolated local phenomenon like wave splash-up.

Figure 4 shows the comparison of computed and measured tsunami runup heights, indicating that the computed results are much smaller than those measured at Riangkroko. The present model with the fault motion only, could not simulate the observed data. This discrepancy is not caused by the runup condition assumed in this model, since the ratio of the measured to the computed values exceeds 5, which is quite large. A propagation process on the steeply sloping sea bottom might cause the significant amplification of a wave, or another geophysical phenomena such as a landslide might have generated a big wave. A second survey conducted in December 1994 found a huge landslide of more than 30 m in height along the coast, about 1 km from Riangkroko (Photo 2), whose location is shown by an asterisk in Figure 2. The effect of a landslide here may also be signficant. For further analysis, a field investigation in this area and a numerical analysis with more detailed offshore topography and bathymetry are required.

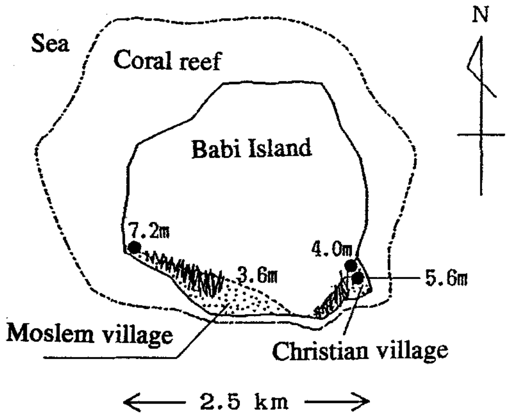

Figure 8
Map of Babi Island. There are two villages on the southern coast of this island. The observed tsunami heights are not extremely high and yet damage to the two villages was considerable.

4. *Damage in Babi Island*

Babi Island

Babi Island (Figure 8) sustained significant damage with 263 casualties out of a population of 1,100. All houses were completely destroyed. Maximum tsunami runup heights were 5.6 m in the Christian village and 3.6 m in the Moslem village. A maximum height of 7.2 m on Babi Island was measured on a cliff in the western side. Although the runup heights were not as high as those at other damaged places, the damage due to tsunamis was quite severe.

Babi Island is about 5 km offshore of Flores Island. It has a conical shape with a 351 m elevation at the summit and is approximately 2 km in diameter. The northern shore faces the Flores Sea and possesses a wide coral reef, while the southern shore, where the two villages were located, has a much narrower reef. Even when strong wind waves and swells of the Flores Sea attack from the north, wave conditions on the southern side are usually calm, because most incoming wave energy is dissipated on the wide coral reef on the northern side (YEH *et al.*, 1993). However, in this event the southern part of the island sustained severe damage due to tsunami currents rather than waves.

Reflected Waves and Hydraulic Pressure

In order to explain why the southern coast of Babi Island suffered severe damage due to the tsunami, a numerical simulation with the same condition as shown in Table 2 was carried out, focusing specifically on Babi Island. Some of the

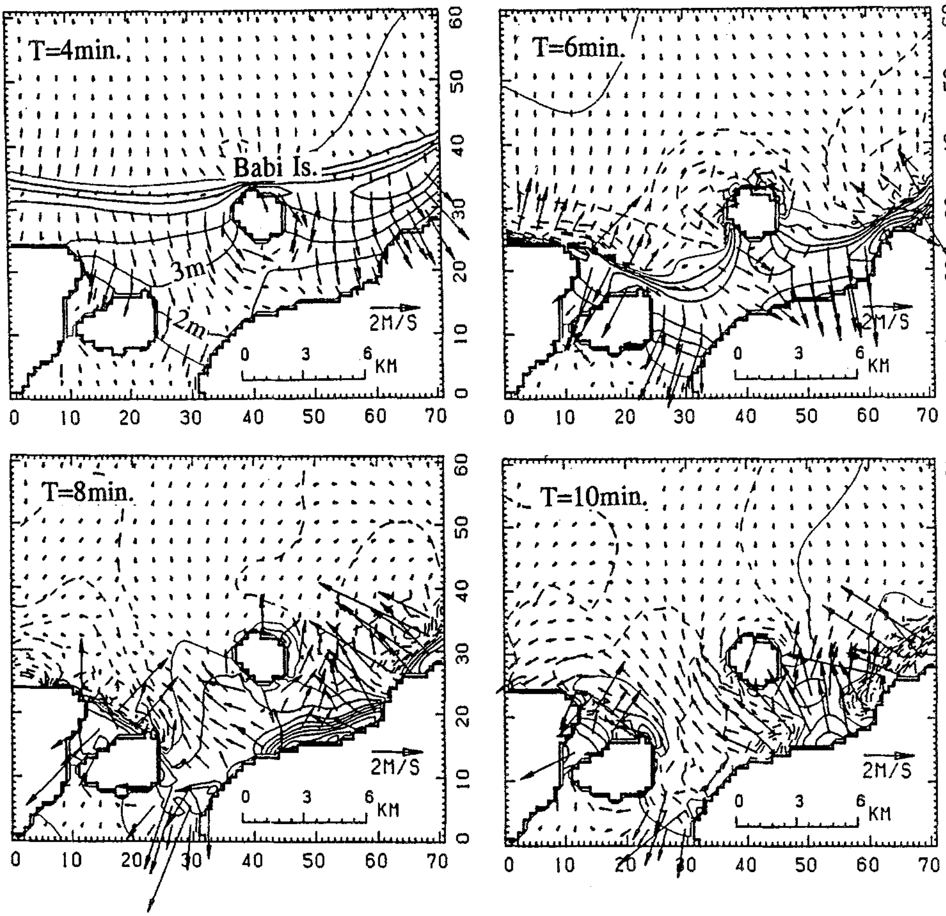

Figure 9
Water elevation contours with intervals of 1 m and current vectors around Babi Island. The first wave was reflected along the northern shore of Flores Island 8 minutes after the earthquake and attacked the southern coast of Babi Island.

numerical results are shown in Figures 9 and 10. Figure 9 shows the water elevation contours and the current vector distributions around this island from 4 minutes to 10 minutes after tsunami generation. Figure 10 shows the time histories of water level, velocity, and hydraulic pressure in front of the Moslem village. The hydraulic pressure is defined as follows (AIDA, 1977);

$$[\text{Hydraulic pressure } (m^3/s^2)] = [\text{Tsunami inundated height (m)}] \times [\text{Current velocity (m/s)}]^2. \qquad (1)$$

HATORI's (1984) empirical result of the relationship between damage to houses and several hydraulic properties, demonstrated that hydraulic pressure is the most suitable parameter to estimate the degree of house damage. Figures 9 and 10

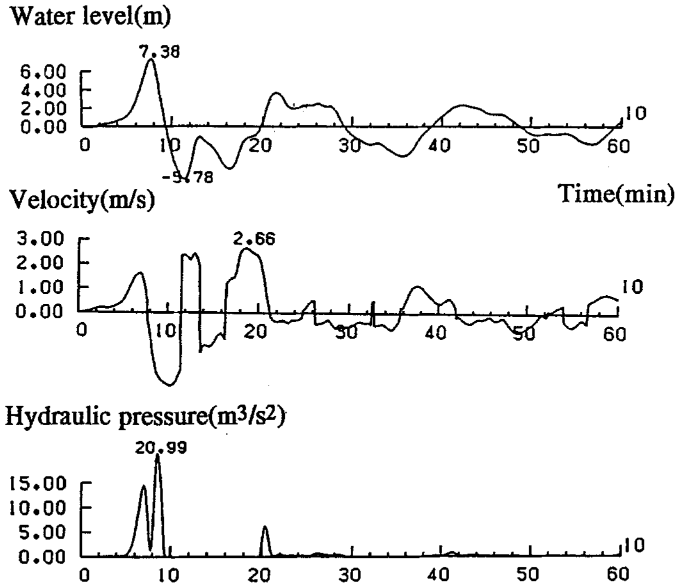

Figure 10

Time histories of water level, velocity and hydraulic pressure. The positive values of the velocity component indicate that the tsunami propagated from the northern side to the southern.

indicate that the first wave attacked the island from the north without high hydraulic pressure. The same wave was reflected off the coast of Flores Island and again attacked Babi Island on the southern part, accompanied by high hydraulic pressure, which is consistent with the eyewitnesses' account. In addition, the island is located at the nodal point of the standing wave, suggesting that the wave height is small whereas the current is large.

Measured and Computed Hydraulic Pressure

We could estimate hydraulic pressure and velocity at Wuring near Maumere by measuring the tsunami traces on the wall of the Mosque (MATSUTOMI, 1993; IMAMURA *et al.*, 1993b). Here most of the wooden houses were destroyed due to the tsunami. Applying the Bernoulli equation, by assuming energy conservation between the front and back of the Mosque, we computed the velocity to be 2.7–3.6 m/s and the hydraulic pressure to be 6.2–15.2 m^3/s^2. This estimation agrees with HATORI's (1984) criterion that hydraulic pressure over 5–9 m^3/s^2 corresponds to damage of over 50%. The present simulation yields a velocity of 2.38 m/s and a hydraulic pressure of 7.70 m^3/s^2, which agrees well with the measured data, and supports the accuracy and reliability of this simulation model. From the numerical model, it is determined that the locations with hydraulic pressure beyond 10 m^3/s^2 are Babi Island, Waibalan, Pantai Lato and Riangkroko, where severe damage was reported. Surprisingly, the hydraulic pressure at Riangkroko is over 30 m^3/s^2.

5. Conclusions

The landslide found on the southern shore of Hading Bay could generate local waves which are substantially higher than those obtained by the tsunami simulation from the fault model only. A new model for wave generation due to landslide, the circular-arc slip model, is proposed. This model reproduced higher runup heights along the coastline than the subsidence model. The tsunami runup height at Riangkroko was extraordinarily high compared to other locations. The wave propagation process on a steep slope of sea bottom as well as other geological agents, such as submarine landslide, could be related to this data. The numerical model reveals that the reflected wave along the northeastern shore of Flores Island is the main cause of severe damage in southern Babi Island. The computed hydraulic pressure and velocity, which correspond well to the measured data at Wuring, are useful in estimating the area of damage due to the tsunami.

Acknowledgements

We express our thanks to the Meteorological and Geophysical Agency of Indonesia (BMG) for their support of our survey. The study was supported by a Grant-in-Aid No. 04306024 for Cooperative Research (A) from the Ministry of Education, Science and Culture, Japan.

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(Received August 18, 1994, revised March 23, 1995, accepted April 8, 1995)