CHAPTER 60

Numerical Simulation of the 1992 Flores Tsunami in Indonesia : Discussion on large runup heights in the northeastern Flores Island

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ABSTRACT - Tsunami source model is disscused by numerical analysis for the 1992 Flores Island, Indonesia. Computed results with the composite fault model with two different slip values show good agreements with the measured run-up 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, which could be the reason of discrepancy between the measured and computed one. The circular-arc slip model proposed in this study for wave generations due to landslides shows better results than the subsidence model. It is, however, difficult to reproduce the tsunami run-up height of 26.2 m at Riangkroko, which was extraordinarily high compared to other places. Two villages located on the southern coast of Babi Island, back side of the tsunami source region, received severe damages. The simulation model shows that the reflected wave along the northeastern shore of Flores Island, accompanying a high hydraulic pressure, could be the main cause of huge damages in the southern coast of Babi Island.

INTRODUCTION

On 12 December 1992, a earthquake of 7.5 Ms and accompanying destructive tsunami struck the northeastern coast of Flores Island (Figure 1). 1,713 casualties and 2,126 injured , half of which were due to tsunami, were reported [*Tsuji et al.*, 1993]. An extremely large tsunami run-up height of 26.2 m was measured at Riangkroko in the northeastern peninsula of Flores Island. There are only two examples in this century --- the 1933 Sanriku earthquake tsunami and the 1993 Hokkaido nansei-oki earthquake tsunami --- in which more than a 20 m tsunami run-up height has been observed.

An International Tsunami Survey Team (ITST) consisting of engineers and scientists from Indonesia, Japan, U.K., Korea and U.S. conducted a field survey

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along the northeastern coast of Flores Island and smaller offshore islands, and measured tsunami run-up heights as shown in Figure 2.

In this paper, two of problems ITST pointed out are selected because of their important role in preventing tsunami disasters in the future. First is that run-up heights at Riangkroko and at Uepadung and Waibalan in Hading bay of 17.3 - 26.2 m and more than 10 m, respectively, are surprisingly larger than those on the western part of Flores Island[Gonzalez et al., 1993] (Figure 2). Second is the damage at two villages in Bali Island, which are located on the back side of tsunami source where usually damage due to tsunami is not large.



Figure 1 Map of tectonic and epicenter of earthquake in Flores Island which is located in the back arc of eastern Sunda and western Banda thrusts.



Figure 2 Measured tsunami run-up heights in meter in the eastern Flores Island and the tsunami source [Tsuji et al., 1993]. A general trend of increasing run-up height from west to east in this region is significant. The symbols of cross indicate the location of landslide in the Hading Bay.

TSUNAMI SOURCE MODEL

Our initial tsunami model uses one fault model, Model-A in Table 1: the quick Harvard CMT solution [event file M121292Y]. Taking into account the tectonics in this region, that is thrust in the back arc [*Hamilton*, 1988], a shallow dip thrust fault as the source with (strike,dip, slip) = $(61^\circ, 32^\circ, 64^\circ)$ is selected. According to the distribution of the aftershocks determined by the United State Geological Survey (USGS), the fault plane is estimated to be 100km long and 50km wide. Thus an average dislocation of 3.2 m can be determined by using a rigidity of 4.0×10^{11} dyne/cm².

| | Mo | Depth | Strike | Dip | Slip | Length | Width | Dislocation |
|---------|---------------------------|---------|--------|---------|-------|--------|-------|-------------|
| | (x10 ²⁷ dyn-cm | 1) (km) | (deg |) (deg) | (deg) | (km) | (km) | (m) |
| Model-A | 6.4 | 15 | 61 | 32 | 64 | 100 | 50 | 3.2 |
| Model-B | | | | | | | | |
| (East) | 1.6 | 15 | 61 | 32 | 64 | 50 | 25 | 9.6 |
| (West) | 4.8 | 15 | 61 | 32 | 64 | 50 | 25 | 3.2 |
| Model-C | | | | | | | | |
| (East) | 1.6 | 3 | 61 | 32 | 64 | 50 | 25 | 9.6 |
| (West) | 4.8 | 3 | 61 | 32 | 64 | 50 | 25 | 3.2 |
| | | | | | | | | |

Table 1 Fault parameter of the 1992 Flores earthquake



Figure 3 Computational region and geometry, countor of water depth, in the northeastern Flores Island. Spatial grid size of 300 m is used.

A numerical simulation of tsunami generation and propagation, the TUNAMI-N1 code [*Shuto et al.*,1990 and *Imamura et al.*,1992], was carried out using this fault model. The area for computation is shown in Figure 3. The lack of detailed topographical data in shallow region and on the land makes it difficult to carry out run-up simulation. Therefore the computed maximum levels along the coastline are directly compared with the measured run-up heights. The computational condition is summarized in Table 2.

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

Table 2 Computational condition

The computed results with Model-A are smaller than the measured run-up heights in the eastern part, suggesting that the slip value on the eastern side of the fault might have been larger than that on the western side. After several trials, a composite fault model with different slip values : 3.2 and 9.6 m was, therefore, proposed [*Imamura & 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 4). The crustal movements estimated by the composite fault model with a depth of 3 km coincides with the crustal deformation measured by *Tsuji et al.* (1993). Computed results using composite model, Model-B and C, are compared to the measured run-up heights in Figure 5, which shows that the numerical model with the composite fault model reproduces well the distribution of the measured tsunami heights along the northeastern coastline of Flores Island, except for the southern shore of Hading Bay and Riangkroko.

Figure 4 Composite fault model [Imamura & Kikuchi, 1994] and its vertical displacement of ground. Moment release in the eastern part is larger than that in the

western part.

Figure 5 Comparison between the measured run-up heights and the computed maximum water level along the northeastern coast of Flores Island. Computed result show a good agreement with the measured one except for Uepadung, Waibalan and Riangkroko.

TSUNAMI IN HADING BAY AND RIANGKROKO

Landslide in Hading Bay

As shown in Figure 5, the measured run-up heights of 10.6 m at Waibalan and 7.6 - 11.0 m at Uepadung in the southern shore of Hading Bay are much higher than those at other places in this bay such as Pantai Lato and Pantai Leta, and the computed results with composite fault model. It is possible that abnormal run-up heights were generated by not only earthquake but another 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, forming a steep and vertical cliff along the present shoreline and its area is approximately 150 m wide and 2 km long. The large run-up heights observed are limited to the area of subaqueous slumps, suggesting a possibility that they were caused by landslide-generated waves rather than tectonic tsunami waves.

Wave Generation Model due to Landslide

Until now several models for wave generation due to landslides, ranging from the inflow volume method and unit-width discharge method [*Ming & Wang*, 1993] to two-dimensional boxes dropped vertically at the end of a semi infinite channel [*Noda*, 1970] have been proposed. Yet, all these methods cannot be applied directly to the present case, because higher tsunami heights were observed not on the opposite side the landslide area but along the landslide and its surrounding area. In addition, the

observed run-up were higher than the level of the top of the landslide. In the present study two models, subsidence and circular-arc slip model (Figure 6), are proposed [Gica, 1994], because the cavity formed by a sudden collapse could generate a wave propagating toward the coast. In the discussion for wave generation due to landslides, the run-up modeling is used. Numerical condition that the averaged depth, 20 m, and height of land, 8 m, is estimated from the field survey, but the radius of circular-arc slip, 30 m, and property of soil are assumed here because there are no data about them. Assuming the same maximum vertical displacement in both models, the computed results showed that the wave run-up height, 3.9 m, of the subsidence model is half that of the circular-arc slip model, 8.2 m. The reason is that the toe of the landslide mass in the circular-arc slip model increases the sea bottom, which causes the disturbances of water surface propagating toward the coastal line. The maximum runup heights of the circular-arc slip model is 8.2 m and almost same as that of the ground level. The above result suggests that the circular-arc slip model is more suitable to reproduce the tsunami of more than 10 m in height. 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 the measured in Hading Bay.

Figure 6 Subsidence (left) and circular-arc slip (right) models for the wave generation due to landslides. The deformation sea bottom is calculated every steps based upon two models. c; soil cohesion, \$\$, soil friction angle, g: gravitaional acceleration.

Riangkroko

An extremely large tsunami run-up was measured at the small village of Riangkroko (Figure 7), where 137 people lost their lives (population 406 prior to the event). The village is located at the mouth of a small river, the Nipar River, with its northwestern side facing the Flores Sea. Offshore from the village there is a remarkable steep slope of sea bottom, which is similar to the case of Okushiri Island in the 1994 Hokkaido Nansei Oki earthquake tsunami. The maximum run-up height measured at Riangkroko was 26 m and the average of heights based on four different tsunami marks was 19.6 m, indicating that the magnitude of the tsunami run-up is probably not an isolated local phenomenon like wave splash-up. Figure 5 shows that the computed results are much smaller than the measured at Riangkroko. The ratio of the measured to the computed values is more than 5, which is considerably large. The reason of such a large run-up height and discrepancy to the computed results should be explained, however no significant geological phenonema such sa landslide at Hading bay was observed on the land. A propagation process on the steep slope of sea bottom could cause the significant amplification of wave, or another geophysical phenomena such as submarine landslide could generate wave. For further discussions, a field investigation on this area and a numerical analysis with the more detailed topography at the offshore and on the land are required.

Figure 7 Inundation area and tsunami run-up at Riangkroko. All houses were completely washed away by tsunami. Numerals in pareuthese are the inundated tsunami heights.

H UGE DAMAGE IN BABI ISLAND

Babi Island

Babi Island (Figure 8) received significant damage with 263 casualties for 1,100 residences, and a complete loss of all houses. Measured tsunami run-up heights are 5.6 m in the Christian village and 3.6 m in the Moslem village. A maximum of 7.2 m was measured on the cliff in the western side of the island. Although the run-up heights are not as high as those at other damaged places, the damage due to tsunamis was quite severe.

Figure 8 Map of Babi Island.

Babi Island is about 5 km offshore from Flores. It has a conical shape with a 351 m summit elevation and approximately 2 km in diameter. The northern shore faces the Flores Sea and has 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, southern part of the island severely received damages due to tsunami current rather than large wave.

Reflected Waves and Hydraulic Pressure

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

[Hydraulic Pressure (m^3/s^2)] =

[Tsunami Inundated Height (m)] x [Current Velocity (m/s)]² (1) It is noticed that current velocity makes effect on hydraulics pressure more than tsunami height.

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 at 8 minutes after earthquake and attacked the southern coast of Babi Island.

Hatori's(1984) empirical result of the relationship between damage on houses and hydraulic properties showed that the hydraulic pressure is the most suitable parameter to estimate the degree of house damages. Figures 9 and 10 show that the first wave attacked the island from the north direction with not a high hydraulic pressure , but the same wave was reflected off the coast of Flores Island and again attacked Babi Island on the southern part accompanied by a high hydraulic pressure. This result is consistent with the eyewitnesses at this island. In addition, the island is located at the nodal point of the standing wave generated along the coast of Flores Island, suggesting that the wave height is small whereas the current is large.

Figure 10 Time histories of water level, velocity and hydraulic pressure. The positive values of velocity component indicate that tsunami propagate from the northern side to the southern one.

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.*, 1993] (see Figure 11). Here almost all of the wooden houses were destroyed due to the tsunami. Applying the Bernoulli theorem by assuming energy conservation between the front and back of the Mosque, we calculated the velocity to be 2.7 - 3.6 m/s and the hydraulic pressure to be 6.2 - 15.2 m³/s². This estimation coincides with Hatori's(1984) criterion that the hydraulic pressure over 5-9 m³/s² corresponds to damage of over 50 %. The result of the present simulation, a velocity of 2.38 m/s and a hydraulic pressure of 7.70 m³/s² agreed with the estimated data well, which supports the accuracy and reliability of this simulation model. In terms of numerical results, the places recorded the hydraulic pressure over 10 m³/s² are Babi Island, Waibalan, Pantai Lato and Riangkroko. Surprisingly the hydraulic pressure at Riangkroko is over 30

 m^{3}/s^{2} .

Figure 11 Tsunami traces on the mosque at Wuring, which are used to estimated the current velocity and the hydraulic pressure.

CONCLUSIONS

The landslide found in the southern shore of Hading bay could generate local waves which are much higher than those obtained by the tsunami simulation with only crustal movement. A new model for wave generation due to landslide, circular-arc slip model, is proposed. This model might reproduce higher run-up heights along the coastline than the subsidence model. The tsunami run-up height at Riangkroko was extraordinarily high compared to other places. The wave propagation process on a steep slope of sea bottom as well as the gcological agents such as submarine landslide could be related to this data. Numerical model shows that the reflected wave along the northeastern shore of Flores Island is the main cause of huge damages in southern Babi Island. The computed hydraulic pressure and velocity at Wuring is well corresponding to the measured one.

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