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REPORT OF THE PORT AND
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Characteristics of Aitape Tsunami in 1998 Papua New Guinea

Tetsuya HIRAISHI

Synopsis

The Aitape Earthquake (M=7.1), Papua New Guinea on July 17, 1998, generated the tsunami attack along the coastline west side of Aitape. The maximum tsunami run-up height was 10 to 15m in the Arop and Warapu villages located on the sand spits at the mouth of the Sissano Lagoon. The tsunami induced the tremendous damages and killed 2,202 people. The survivors in the damaged villages were relocated to the newly constructed villages away from the shoreline of the lagoon. From Sep.15, 1999, a special team was dispatched to the remote villages to give the information on the scientific explanation of the generation mechanism and energy concentration of the tsunami to the lagoon area. This paper describes the activities and results of the team in the Aitape region. The effective methods to rebuild and to maintain the relocated villages is discussed, and the warning system applied to the local area with no electricity is suggested.

Numerical tsunami simulation is carried out with an assumption of initial landslide with the volume calculated for the area of 5 km by 5 km and the depth of 20m. The estimated tsunami run-up heights agree with the height distribution obtained in the field survey.

Key Words: Tsunami, Field survey, Numerical simulation, Underwater landslide, Papua-New Guinea

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港湾技術研究所報告
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１９９８年パプアニューギニア津波の特性

平石哲也

要　旨

1998年7月18日にパプアニューギニア北岸で生じた津波は，地震マグニチュードが7.1と比較的小さかったにもかかわらず，沿岸で15m以上の津波高となり2000名以上の人名を奪う被災を生じた．現地でのヒアリング等の調査から，地震に励起された海底地滑りによる津波である可能性が大きくなったので，5km四方の海底地盤が20m陥没した海底地滑りを仮定して，津波の数値計算が実施された．計算結果は，現地調査で得られた津波の痕跡高の分布と一致し，海底地滑りによる津波計算モデルの適用性が検証された．

キーワード：津波，現地調査，数値計算，海底地滑り，パプアニューギニア

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1. Introduction

On the evening of Friday, 17 July 1998, a large tsunami attacked the north coast of the island of Papua New Guinea just west of Aitape. The magnitude of the earthquake (M) was estimated to be 7.1 in the Richter scale by the seismic observation carried out around the Pacific Ocean. The tsunami waves completely destroyed three densely populated villages that were located on the sandbar that fringes Sissano Lagoon, destroyed most of a fourth village further west, and swept away the ground church at Sissano mission that had stood for more than 70 years. The waves also damaged villages along the coast east of the lagoon as far as Aitape and the mouth of the Raihu River.

Figure 1 shows the location of damaged villages around the Sissano Lagoon. Rescue efforts commenced on Saturday, July 18, morning and accelerated through the following days (Davies, 1998). The international survey team was dispatched about two weeks later the earthquake to have the field survey mainly for getting information of tsunami run-up height along the damaged area. **Figure 2** shows the tsunami run-up height distribution from Aitape to Vanimo coast (International tsunami survey team, 1998). The maximum run-up height was obtained at Arop village located on the sand spit in front of the Sissano Lagoon. The height is extremely large compared with the tsunami height expected for the earthquake of the scale M=7.1. The underwater landslide is assumed to be a source to generate such large tsunami run-up and concentration to Sissano area. The comparison of numerically simulated tsunami heights and observed heights is done to evaluate the applicability of the underwater landslide tsunami modelling.

Table 1 shows the suffered population in the devastated area. The number of life damage was reported by the West Sepic State government in the regional tsunami mitigation meeting. For the survivors there was the grief at the loss of loved ones, confusions, rumor and the fear that another tsunami would strike. The scientific explanation for tsunami generation is inevitable to rescue the anxiety for rehabilitation in the newly relocated villages. Some inconveniences in life also happen in the newly rebuilt villages. The special survey was carried out to make a scientific explanation for tsunami generation and concentration to the Sissano area. The regional meeting was continuously held

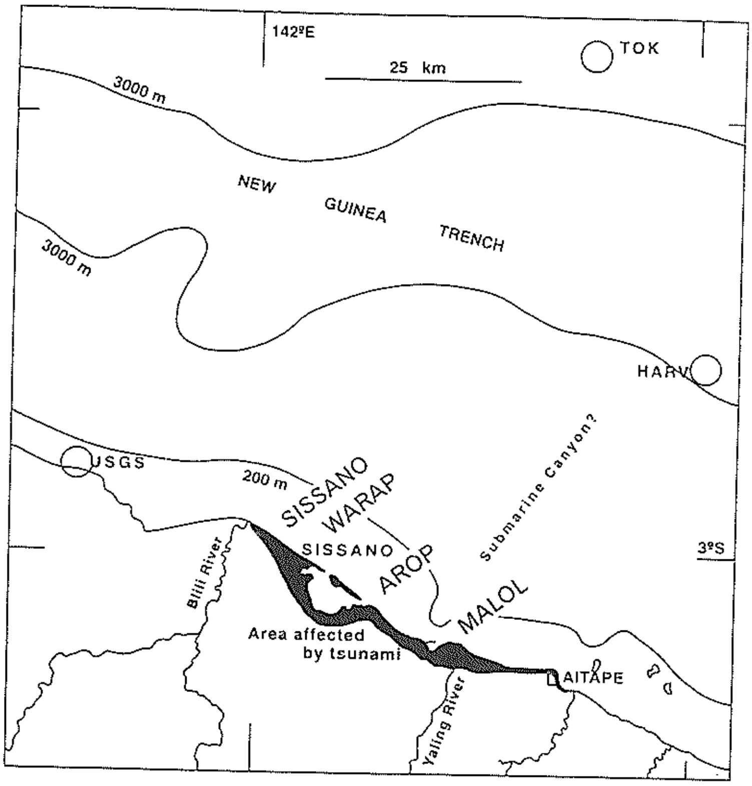


Figure 1 Location of damaged area by 1998 Aitape Tsunami (Davies, 1998)

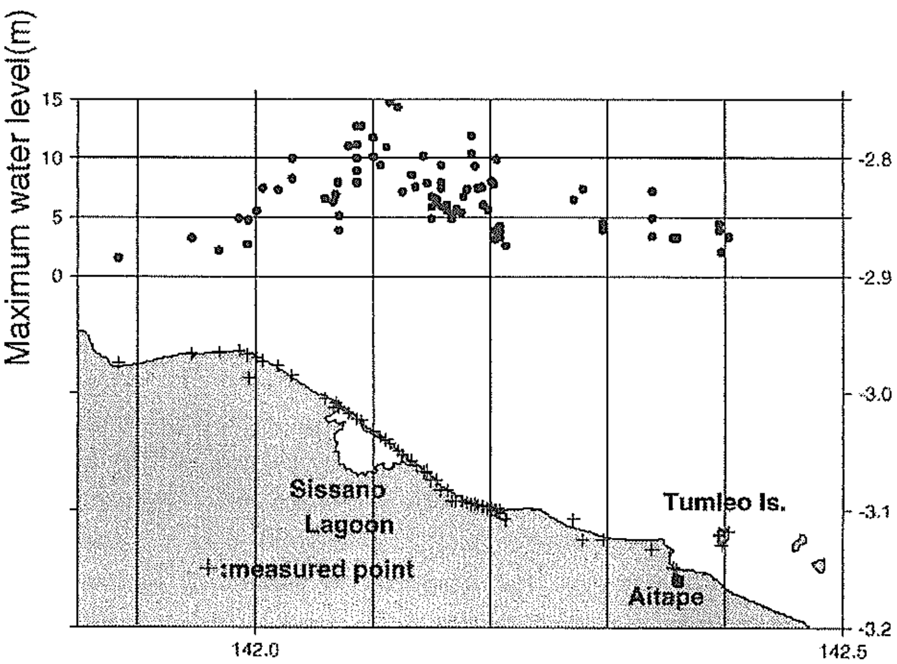


Figure 2 Tsunami run-up height along Aitape west coast (International tsunami survey team, 1998)

Table 1 Human damage in Sissano area

village	population	dead	human risk (%)
Malol	4042	126	3.1
Arop	2382	874	36.7
Barup	1991	108	5.4
Sissano	2306	128	5.6

to resolve the question that the local people has in mind. The paper secondary describes the field survey of rehabilitation of the re-located villages and the possibility of re-location to coastal areas. The discussion and agreement in the regional tsunami mitigation meeting is explained.

2. Tsunami Hazard and Field Survey

The 1998 Aitape Earthquake (M=7.1) on July 17 generated the tsunami attack along the coastline west side of Aitape. The maximum tsunami run-up height was 10 to 15m in the Arop and Warapu villages located on the sand spits at the mouth of the Sissano Lagoon.

Two weeks later the tsunami attack, the international tsunami survey team was dispatched for ten days to the suffered area as mentioned before. The team survey results demonstrate that the tsunami heights was much larger than those expected for the earthquake of the scale M=7.1. The epicenter is estimated about 30km off the shoreline.

However the final determination of the location of epicenter has not been done because the lack of the seismic data on the coastline of the Papua New Guinea itself. In order to investigate the main cause of such large tsunami waves, the following survey has been conducted. The author has arranged the results by the personal communication with each research institute.

1) The first tsunami survey team investigated the tsunami arrival time by the hearing from the survivors. The first tsunami waves came to the coast 15-20 min. after the earthquake shock. The interval time is 10-15 min. longer than the tsunami arrival time caused by the earthquake fault model normally employed to reproduce the incident tsunami waves.

2) The Japan Maritime Science and Technology Center (JAMSTEC) investigated on the November 1998 the detail water depth contour and sea bed topography. They suggested the existence of deep sea bed canyons and many sharp cracks on the steep seabed slope. **Figure 3** shows the contour of water depth obtained in the survey by JAMSTEC. In the figure of the depth contour, the shallow terrace is expanded in front of the Sissano Lagoon. In both sides of the terrace land, the steep valleys are found. **Figure 4** shows the typical cross section of terrace topography. The water depth becomes suddenly large at the just edge of terrace. The new cracks on the seabed taken in the submarine camera suggested the possibility of a huge land slide after the first earthquake shock.

3) The geological survey team from the University of California carried out the ultrasonic signal survey on the terrace land in August, 1999. Their seismic survey cleared the existence of a boundary under seabed layer. From the initial stage of the theoretical investigation on the tsunami mechanism, they insist the old mud layer is covered with the other material layer (Bruce et al.,1998). Those layer is not determined as the

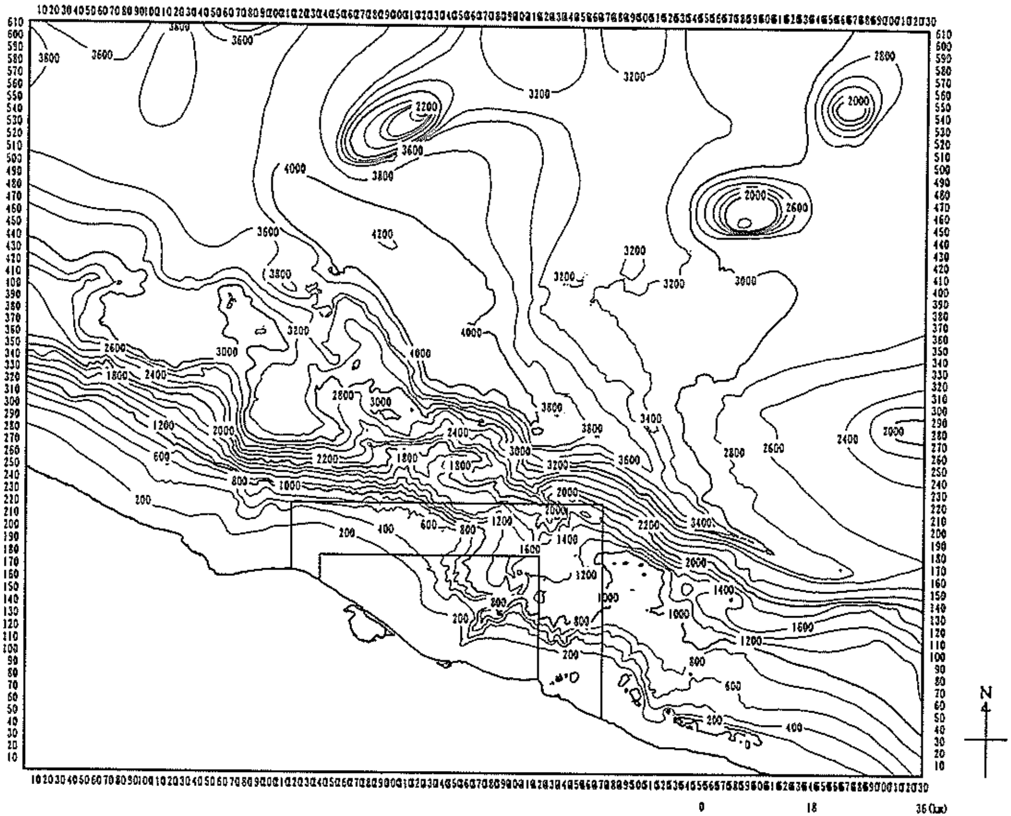


Figure 3 Water depth contour obtained by seismic survey of JAMSTEC

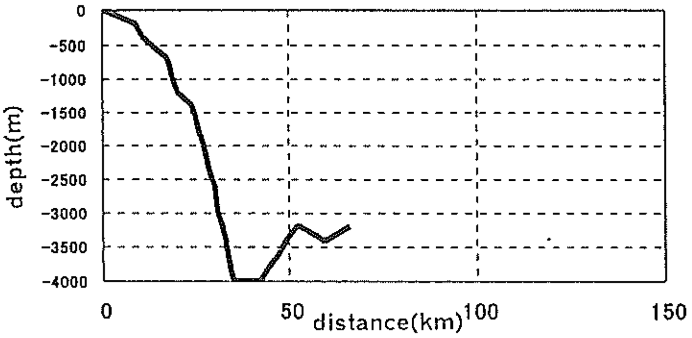


Figure 4 Cross section offshore Sissano lagoon

new accretion by the landslide after earthquake. The possibility, however, of the production of new mud layer by landslide is very high.

Therefore, we assume hereby the occurrence of large size landslide of silty layer at the steep seabed. Such silty layer is accumulated on the seabed by the flow debris and mud brought by the large rivers facing to the northern coast. The water depth data offshore Sissano lagoon was obtained by JAMSTEC survey only in the water area deeper than 200m. Therefore, no detail water depth information in the area shallower than 200m. We made the proper water depth data according with the rough chart published by the Canadian Navy. **Figure 3** includes such modified depth contour information.

3. Tsunami Run-up Height Simulation

According to the field survey and geographic investigation, the generation of landslide by the first earthquake is suggested. Therefore, I introduce the motion of sea bed by landslide into the normal earthquake fault model. In this section I tried to simulate the tsunami run-up height along the coastline of the Sissano Lagoon. The tsunami simulation model is described by Goto et al.(1993). **Figure 5** shows the computational coordinate system in the tsunami simulation. The following momentum and continuity equations are resolved in the finite difference method. In the following equations, Eq.(1) corresponds to the continuity one and Eq.(2) and (3) represents the momentum equation in the x- and y-coordinate respectively.

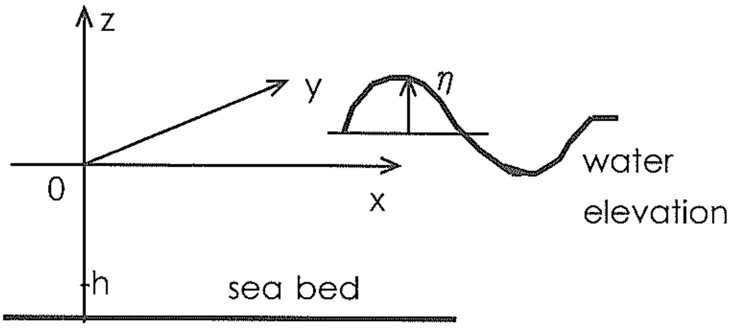


Figure 5 Coordinate system in tsunami propagation simulation

$$\frac{\partial \eta}{\partial t}+\frac{\partial M}{\partial x}+\frac{\partial N}{\partial y} = 0 \tag{1}$$

$$\frac{\partial M}{\partial t}+\frac{\partial}{\partial x}\left[\frac{M^2}{D}\right]+\frac{\partial}{\partial y}\left[\frac{MN}{D}\right]+gD\frac{\partial \eta}{\partial x}+\frac{f}{D^2}MQ = 0 \tag{2}$$

$$\frac{\partial N}{\partial t}+\frac{\partial}{\partial x}\left[\frac{MN}{D}\right]+\frac{\partial}{\partial y}\left[\frac{N^2}{D}\right]+gD\frac{\partial \eta}{\partial y}+\frac{f}{D^2}NQ = 0 \tag{3}$$

where, (x, y) represents the spatial coordinates on the water surface and t, η ,h, g, f indicates time, initial water depth gravity acceleration, energy dissipation coefficient on sea bed respectively. D represents the total water depth calculated as $h+\eta$. M and N represents the momentum flux on the x- and y-direction respectively. Q correspond to $(M^2+N^2)^{1/2}$.

In the simulation, the tsunami profiles in the shallow water area are expected by calculating the above equations at each time step when the initial water elevation deformed by the offshore earthquake. The elastic deformation theory derived by Manshinha and Smylie(1971) is applied to estimate the variation of sea bed topography by the earthquake land fault. The initial distribution of water elevation is assumed to be same to the elevation of sea bed topography. **Figure 6** shows the image of initial tsunami profile at the offshore tsunami source area. In the figure the rigid curve represents the initial water elevation induced by the normal earthquake land fault.

For the underwater land slide, the accurate field data has not been obtained. Along the Japanese coast line, a sounding survey has been carried out in the Nankai-trough offshore Tokai district (Tokuyama et al., 1999). **Figure 7** shows a cross section of sea bed layer at the edge of the Nankai-trough. The small land faults are clearly expressed in the sounding test. The faults are observed in the area with the width of 5 km and the under water slides have occurred in the range of 5 km width. The height of one under water slide is not obtained from the sounding test. The land fault is generally generated along the circular failure curve. **Figure 8** shows the image of the circular failure curve on the inclined sea bed. I assume the length of circular failure curve becomes much larger than the depth of sea bed mud layer deformed by the landslide. Therefore, the shape of deformed layer is approximated by the slight rectangular as shown in Figure 8. In the figure, the doted curve and broken line represents the original circular failure curve and approximated deformation profile respectively. The depth of the circular failure is not determined with the present field data. I assume the depth of deformation as 20m as the computed tsunami heights agree with the observed ones. In this paper, the mass volume of 5 km × 5 km with the depth of 20m is assumed to have moved at the moment after the shock to the onshore from the offshore steep underwater slope. The deformed sea bed topography is assumed to give the influence directly to the surface water elevation. The initial surface water elevation for tsunami simulation is modified to the profile indicated by the broken line in **Figure 6**.

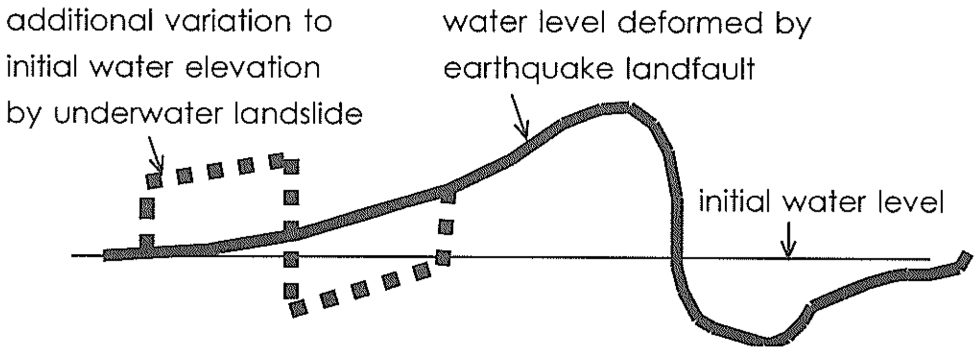


Figure 6 Image of initial water surface variation induced by earthquake and landslide

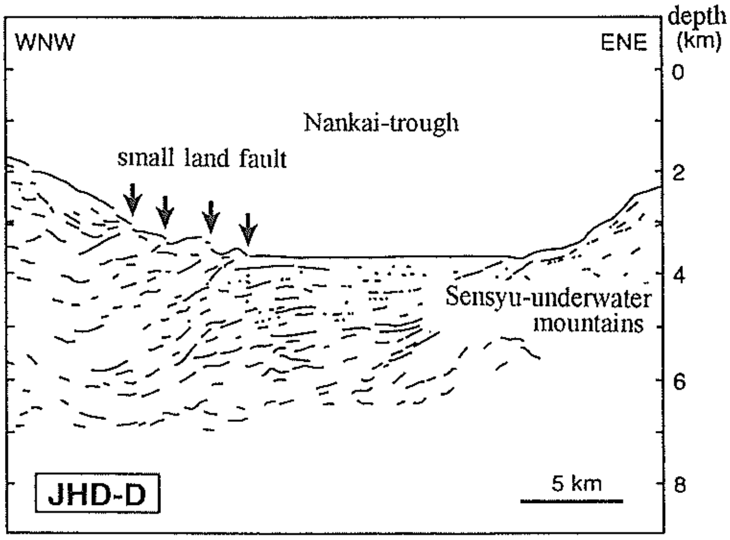


Figure 7 Sounding test offshore Tokai (Tokuyama et al., 1999)

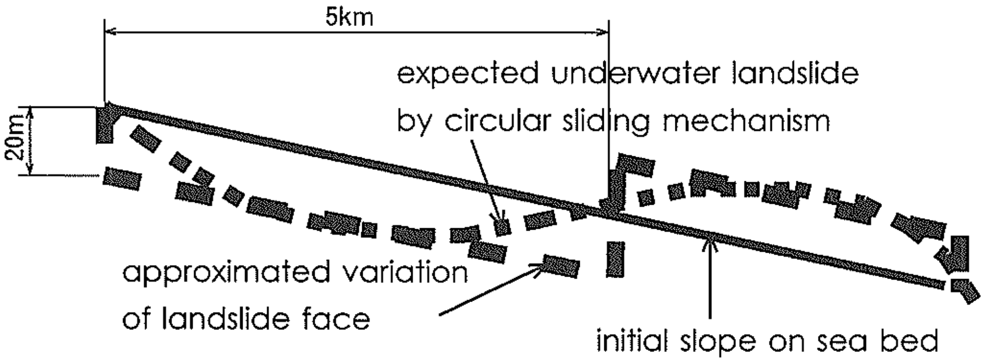


Figure 8 Approximation of underwater landslide by simple plate

Table 2 Parameter of land fault model for M=7.1 earthquake

latitude of fault base point	2° 35' S
longitude of fault base point	142° 5' E
fault length (m)	30
fault width (m)	10
depth of upper edge (km)	1
slope angle (deg)	15
direction of fault line	N 105° E
sliding volume	3.0
vertical component (m)	3.0
horizontal component (m)	0.0

Table 2 shows the parameter of land fault expected by the normal earthquake of M=7.1. The intensity of parameter is determined in the empirical method proposed by Sato et al.(1989). **Figure 9** shows the initial water elevation by the assumed land fault offshore the Sissano Lagoon. In the computation model, the outside area is represented in the grids 200m long, and the middle range area is expressed in 100m grid. The shallow water area is computed in the grid 50m wide. In the finest region with 50m grid, the water run-up is computed. The height of sand spit area is estimated from the map made by the Australian Navy.

Figure 10 shows the comparison between the tsunami run-up heights observed in the field survey and estimated only in the normal earthquake land fault tsunami generation model. The estimated tsunami heights much smaller than the observed heights. Therefore, the other source for the tsunami generation like the underwater landslide is necessary to compute the large tsunami run-up heights in the Sissano area.

The land slide with 5×5 km is assumed to be located at the edge of earthquake fault as shown in **Figure 9**. The exact location of landslide should be assumed to induce the proper distribution of tsunami run-up heights. I assumed at first the serval locations for the under water landslide. **Figure 11** shows the initially assumed location of under water landslides. After serval numerical calculation and comparison with the observed tsunami run-up height distribution, we employed the location No.11 as the most appropriate location for underwater landslide. The mass of seabed is replaces offshore at the same time to the generation of the land fault. Therefore, the initial water distribution shows the local raise by the removed land mass.

Figure 12 shows the computation results for tsunami height along the coast. In this case, the mass with the length of 5 km and the width of 5 km with 20m depth is replaced at the moment after the shock to the offshore side. **Figure 12**(1) shows the maximum tsunami height is the computational area with 50m grids. **Figure 12**(2) shows the comparison of the observed and expected tsunami run-up height between Aitape and Vanimo. The tsunami waves are induced by the displacement of the submarine topography by the land fault generated by the earthquake and a local landslide

latitude of fault base point	2 ° 35' S
longitude of fault base point	142 ° 5' E
fault length(km)	30
fault width(km)	10
depth of upper edge(km)	1
slope angle(°)	15
direction of fault line	N105 ° E
sliding volume	3.0
vertical component(m)	3.0
horizontal component(m)	0.0

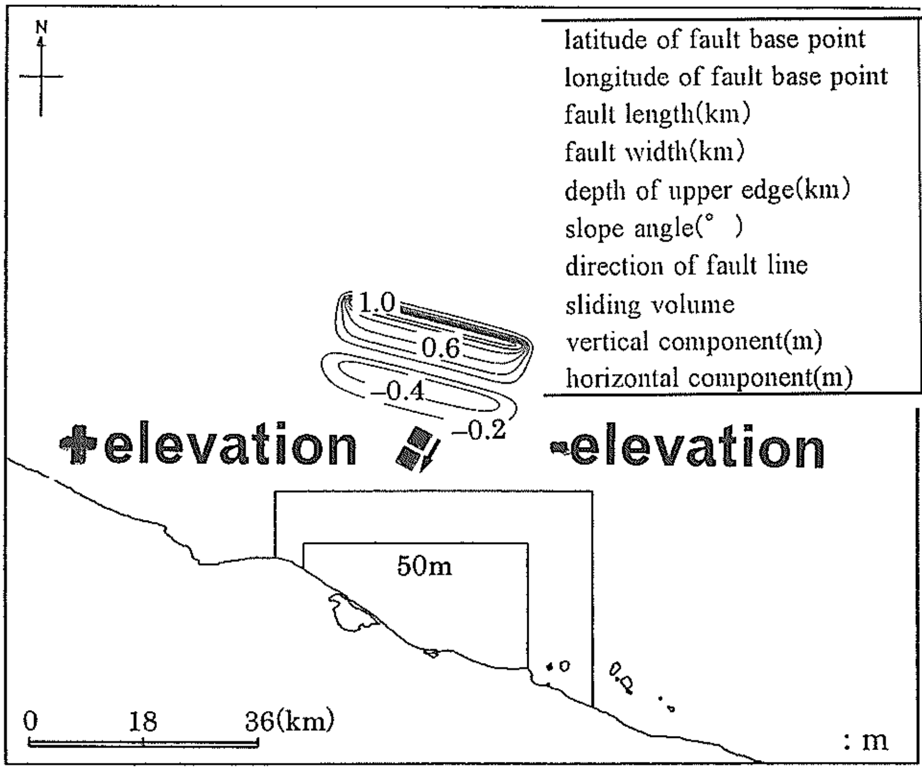


Figure 9 Initial water elevation by earthquake and location of landslide

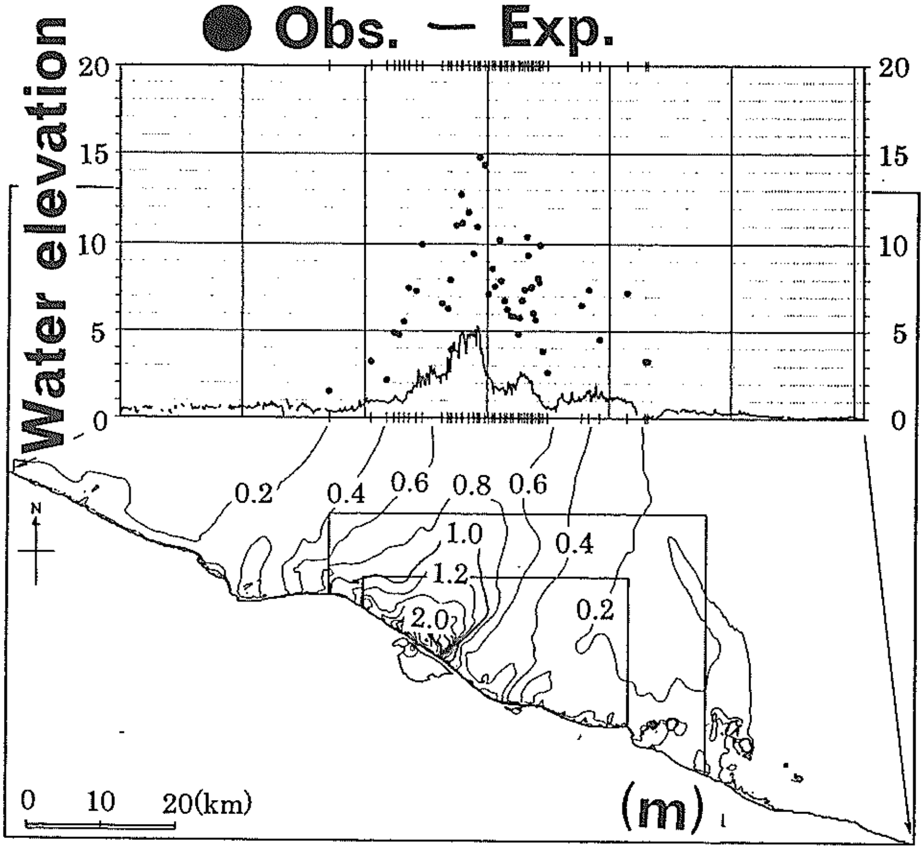


Figure 10 Tsunami run-up height estimated in the earthquake fault model

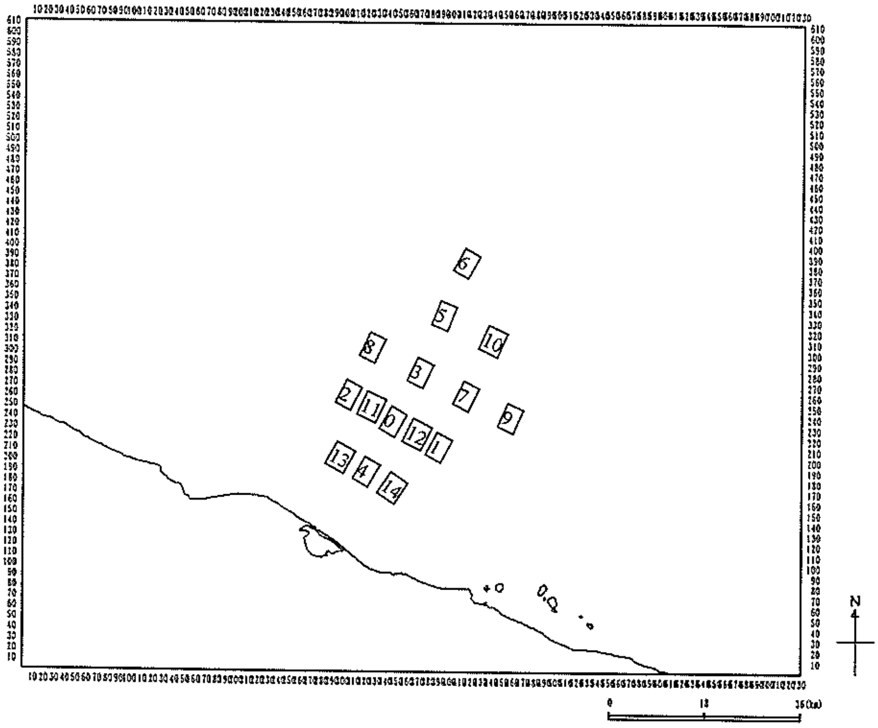
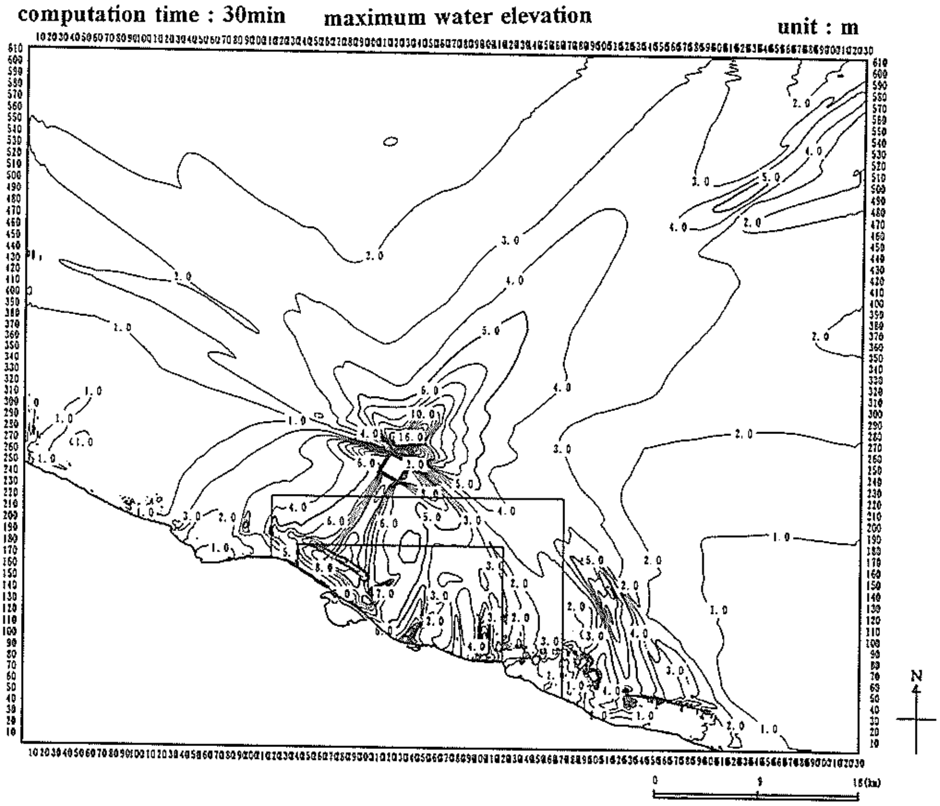
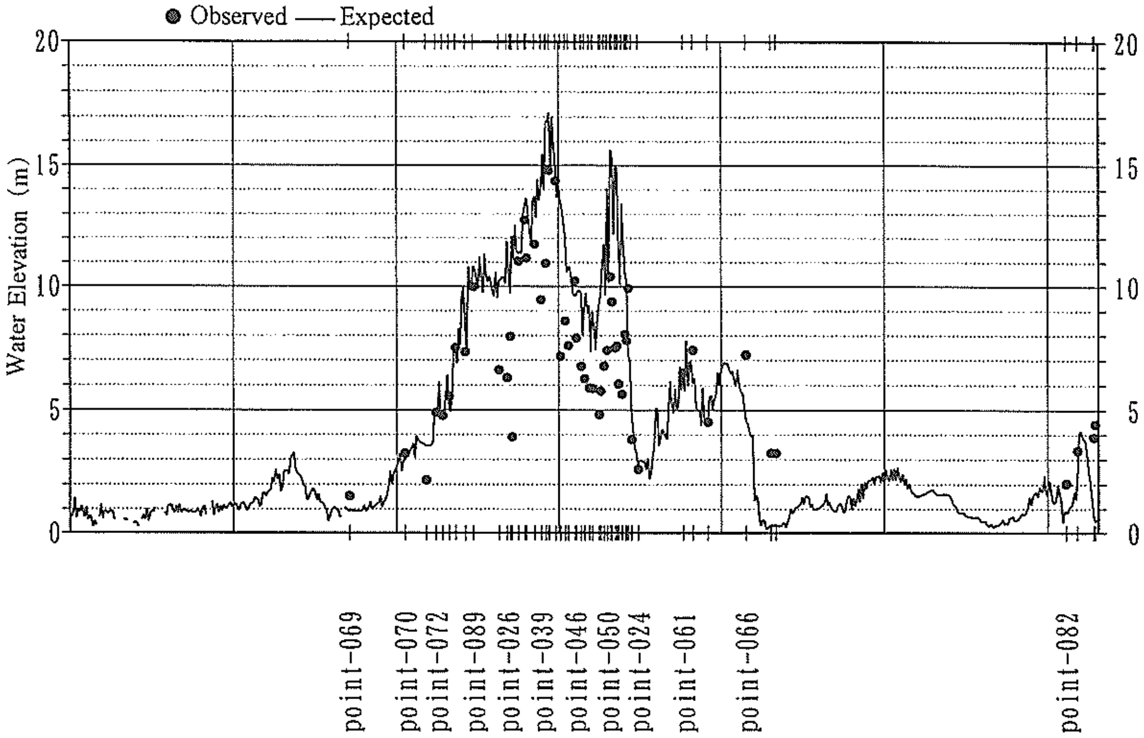


Figure 11 Location of possible underwater landslide offshore Sissano lagoon



(1) Computed height distribution



(2) Comparison with observed tsunami run-up height

Figure 12 Maximum tsunami height generated by underwater landslide along coast of Sissano lagoon

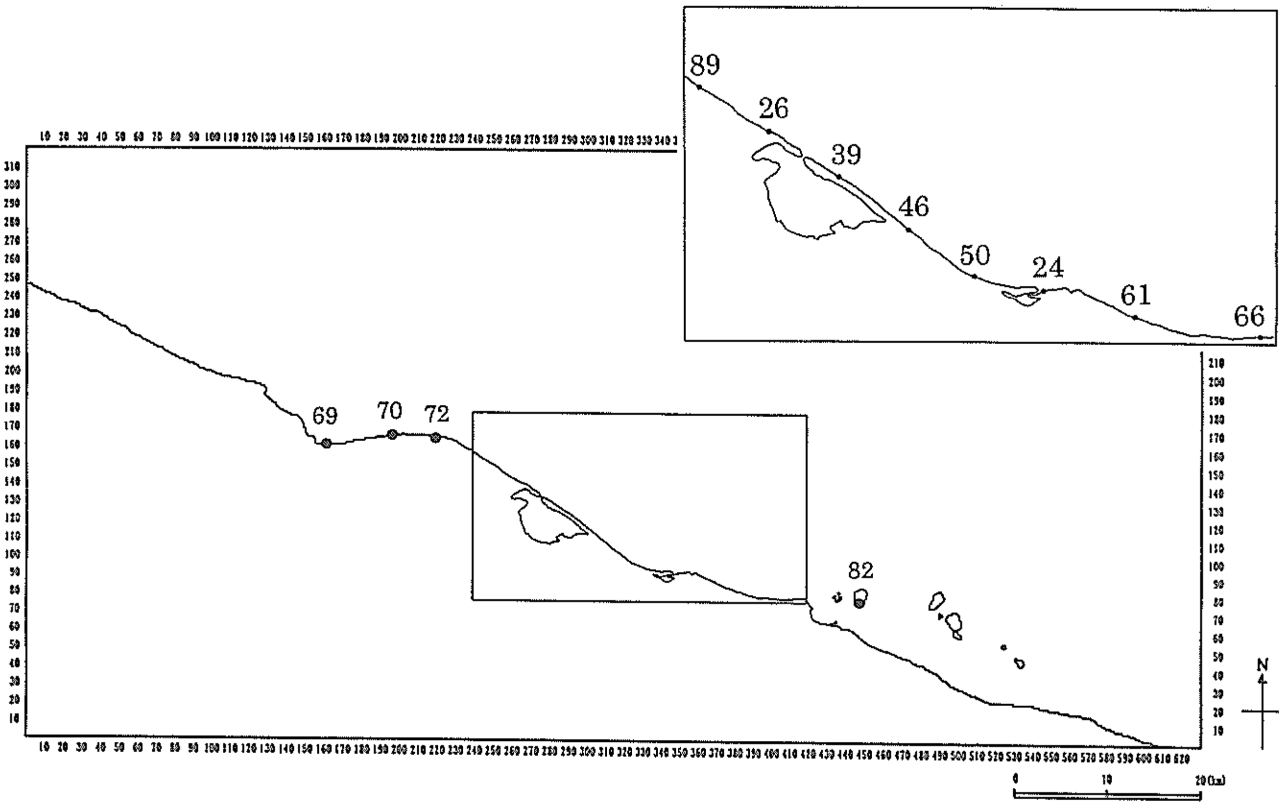


Figure 13 Location of computation point number along Sissano coast

generation. Such large replaces soil volume is expected to be unrealistic, so more detail study for the sea bed topography is essential to determine the reason of the tsunami generation. The location number of **Figure 11** corresponds to the number indicated in **Figure 13**.

The tsunami run-up heights along the coast line agree with the observed distribution from Aitape to Vanimo as shown in **Figure 12**(2). The maximum computed tsunami height is 15m and it is slightly smaller to the maximum tsunami height at the sand spit on the Sissano Lagoon. So the assumption of mass landslide is necessary to get the agreement in tsunami height distribution along the sand spits on the Sissano Lagoon. Under the present survey information, the large volume of landslide generation is most appropriate to explain the tsunami height distribution along the coastline. As well as the generation of land slide, the topography in front of the lagoon causes the concentration of wave energy by refraction. As shown in **Figure 3**, the shallow seabed on the terrace in front of the lagoon and the deep valleys at both sides of the terrace easily cause the refraction of tsunami waves. The refracted tsunami waves are concentrated at the sand spits of the lagoon. Such interactions in the terrace topography become a important reason to induce the huge tsunami waves at the sand spit of the lagoon. The more detail survey for the contour of water depth sallower 200m is planned by the Australian Navy in the near future.

4. Disaster Mitigation Program

The tsunami induced the tremendous damages and killed 2,202 people. The survivors in the damaged villages were relocated to the newly constructed villages away from the shoreline of the lagoon (Papua New Guinea Pacific, 1999). From September 15, 1999, a special international team was dispatched to the remote villages to give the information on the scientific explanation of the generation mechanism and tsunami energy concentration to the lagoon area. The team had seminars at new Arop, Malol, Barupu and Olbrum (Sissano) villages shown in **Figure 14**.

The team showed the basic mechanism of earthquake faults and the induced landslides in the offshore region because some local people believe the tsunami was generated by the attack from enemies or the bombing in the sea. The newly investigated phenomena on the tsunami were introduced to the village people by the team. It helped the local residents understand the natural disaster mechanism. Especially the convergence of tsunami waves to the lagoon area by refraction was discussed with keenness. The establishment of warning system for natural disasters was also suggested.

The future disaster prevention method was discussed in the regional hazard mitigation meeting in Madang on September 25 ~ 28, 1999 after the team completed the discussion with people in the remote areas. The representatives from survivor's villages, Catholic authority, governmental officers and some scientists actuated to determine the future rehabilitation planning.

The paper in the following describes the discussion results in the programed meeting and introduce the author's opinion to protect the tsunami hazard along the PNG(Papua New Guinea) coastline. The detail discussion and suggestion will be published at other opportunity. In this paper, we describe some mitigation program for future tsunami attacks. The mitigation program needs some budget mainly from the governmental side. The international cooperation was also suggested. In the public awareness meeting at first the relocation of the village to the coastline is discussed.

According with the earthquake and tsunami record filed in the Papua New Guinea Geotechnical Research Institute, the earthquakes with tsunami have occurred about every 10 years in the coastline. Appendix shows the history of tsunami around the Papua New Guinea coastal area. All tsunamis generated the wave run-up heights less than 2m, however the record of the earthquake and tsunami suggests the high probability of generation of tsunami in the coastline. The serious tsunami prevention program should be discussed to protect the dangerous areas.

The following prevention images are suggested in the mitigation meeting ;

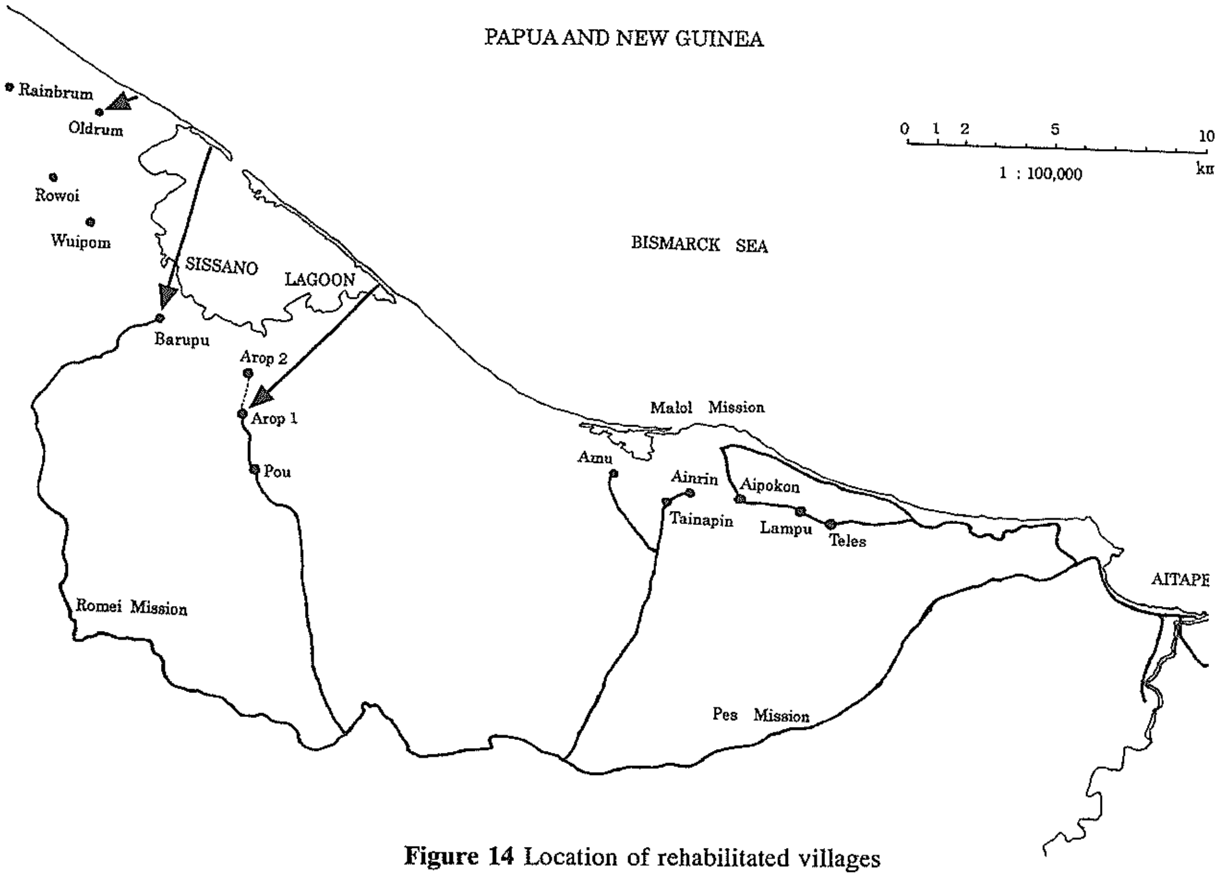


Figure 14 Location of rehabilitated villages

1) **Figure 15** shows the dangerous area on the sand spit extended in front of the lagoon. This area may be attacked by the first tsunami waves. The residents are not able to escape to the hilly area in a few minutes, therefore the land on the sand spit is very weak as the mitigation area for tsunami protection. The relocation and rebuilding of the new villages should be avoided in the future. Only the temporary fishery base is permitted to built to moor the small fishery boat.

2) A small tower should be constructed as the memory of tsunami damages and a cenotaph for dead people. Such memorial marks may be useful to remind the people of the damage of tsunami and the importance for the alarm system in the possible earthquake in the future. Whenever the people take a look of the memorial lights or stone tower, the importance of early escape is reminded. Also the education of tsunami phenomena and the damage experiences in elementary schools are necessary to remind the importance of the smooth escape in coastal zone to the people. The tsunami issues should be included in the textbook of the elementary or junior high school in Aitape region.

3) **Figure 16** explains the growing up the greenbelt composed of mainly coconuts, mango and mangrove trees in sand beaches. The width of green belt perpendicular to shore line should be more than 300m because some scouring in sandy beaches by tsunami flow are found at the places 300m apart from the shoreline. As shown in **Photograph 1** in the damaged area, the coconuts trees remained even for the case that all wooden houses were washed away by the tsunami waves. So, the dense green-belt may dissipate the power of tsunami flows. **Photograph 2** shows the remained house in the Sissano village. The local people explained the dense coconuts trees surrounding the storage houses protected the destroy of it even if the other village buildings were completely swept by the tsunami. The necessary density of greenbelt should be investigated in the experiment and numerical simulation in the near future, but the existence of one storage house shows the possibility of the greenbelt to reduce the tsunami flow pressure described by the η (tsunami run-up height) × μ^2 (tsunami flow speed).

4) **Figure 17** shows the possibility of the relocation of new villages. The sand spit is dangerous to tsunami attack but the coastal area in Malol and West Aitape is employed as the relocated area. Usually, the relocation point is at least 500m apart from coastline. Because the accumulator and scour was surveyed in the area 500m apart from shoreline after the tsunami run-up in the Sissano area, the minimum safety distance from the shoreline is expected to be at least 500m.

5) **Figure 18** shows another mitigation image proposed by the authors. The images show the raising the land level for the villages. The construction time may become longer compared with the other relocation methods. If we raise the level of land up to 7m, the tsunami wave may be broken prior to reaching the raised land. Therefore, main energy of tsunami becomes very small in front of the relocated area. Of course, some distance from the shore line is essential to reduce the tsunami flow speed.

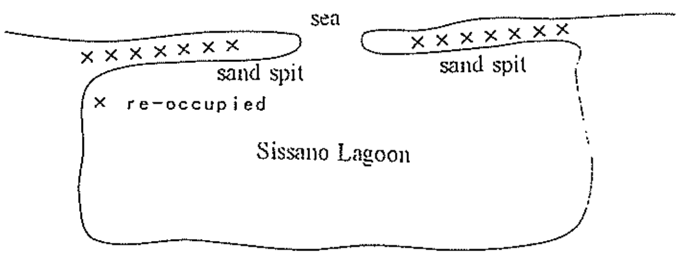


Figure 15 Dangerous area on sand spit

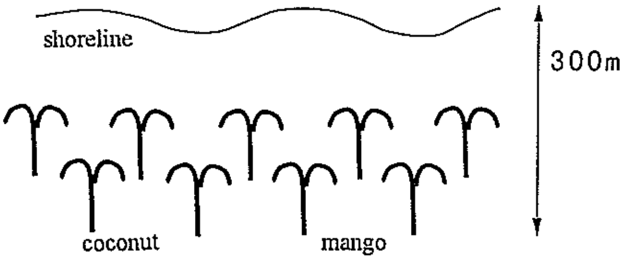


Figure 16 Image of greenbelt protection zone

Photograph 1 Remained coconuts in devastated area

Photograph 2 Protected local house by dense coconut trees

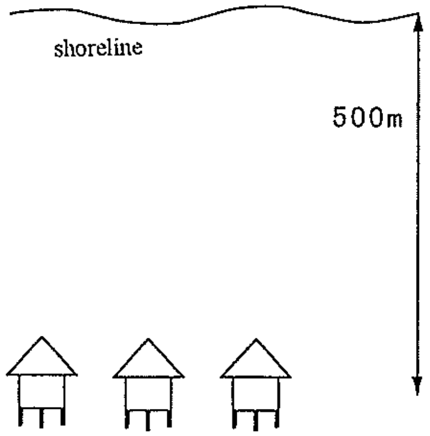


Figure 17 Relocation point of fisherman's village

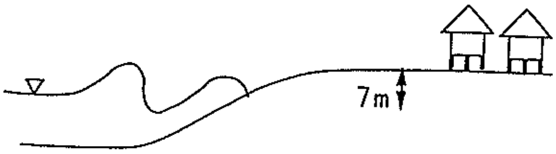


Figure 18 Raise of land level

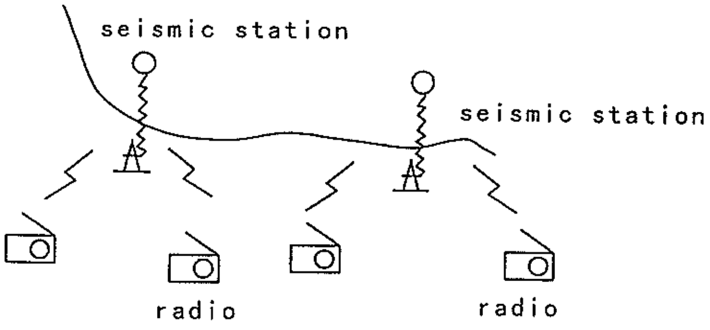


Figure 19 Regional warning system

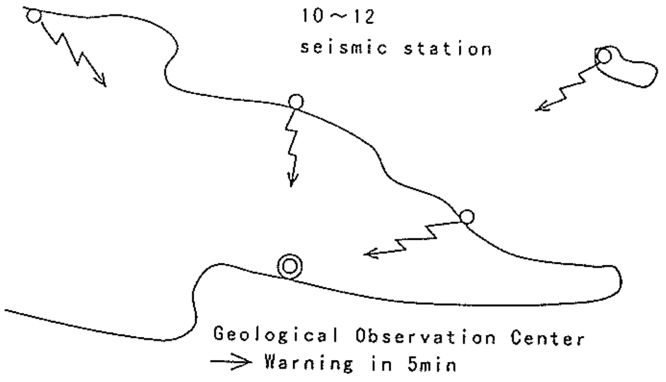


Figure 20 Nationwide natural hazard warning system

6) **Figures 19** and **20** show the regional and nationwide alarming and warning system in the preparation for the future tsunami attack. **Figure 19** shows the regional warning system employing radio distribution. Along the coastline for Aitape to Vanimo, two seismic survey stations are to be established hopefully by the financial assistance from overseas countries. The seismic station is connected to be radio station. When the seismic station may catch the initial earthquake, the alarm is immediately broadcasted from the radio station. In this alarming system, a radio is distributed to each local village people. So each village residents are able to catch the information of the earthquake and tsunami and prepare the escape to the hilly places. The radio network is employed as the education and information method in the normal days. The total cost is expected to be about $50,000.

Figure 20 shows the similar nationwide natural hazard warning system to be established by the support from the overseas countries. In the system 10 ～ 12 seismic observation stations with seismic sensors and tidal gages are constructed along the coast line of PNG area. The obtained information is immediately sent to the geological observation center in Port Moresby. The observation center analyses the obtained data and issues warning to the whole areas of the country in 5 min. The warning for the natural disaster may be caught in the local governmental warning station and each local village offices. Such nationwide alarming system is necessary to develop the hazard mitigation ability of PNG on the future. However, the total cost is not so small and the financial support is essential.

7) The hydraulic detail study to expect numerically the reduction by greenbelt of the tsunami flow pressures becomes another warning method. A long hydraulic channel is employed to measure the reduction of the tsunami height in the greenbelt. The density ρ of greenbelt is another factor to determine the reduction ratio of the tsunami pressure. Such experiment is hopefully carried out as a collaboration works between the PNG researchers and the foreign researches. Through the experiment, we will describe the experimental formula like $H_{out}=f(\rho)\ H_{in}$ to estimate the tsunami pressure behind the greenbelt. Where H_{out}, H_{in} and $f(\rho)$ represents the incident and transmitted tsunami heights and an experimental formula respectively.

5. Discussion

For deriving clear conclusions, the observed data on the variation of sea bed topography after earthquake shaking is enough. The additional survey is necessary to estimate the accurate deformation of sea bed layer by the landslide.

Therefore, the discussion and suggestion are expressed in the paper. The following suggestions were derived in the field survey and numerical simulation for the underwater landslide tsunami in Papua New Guinea.

(1) The observed tsunami run-up heights are much higher than the heights expected only in the normal earthquake land fault model. The additional sources should be assumed to derive such large tsunami heights along the Sissano coast. The underwater landslide is able to be considered as one of such additional sources to induce the Aitape tsunami.

(2) The slight plate is applied to approximate the circular failure curve induced in the underwater landslide. The length, width and depth of the deformed plate is assumed to be 5 km, 5 km and 20m respectively according with the comparison of the expected and observed tsunami height distribution.

(3) The tsunami survey results by the international scientific teams are summarized. The expert team was dispatched to give the scientific information of the resent study to the relocated villages around the Sissano area. The team activity was helpful for the village people to establish the future mitigation planning.

(4) Some field survey in the Sissano area so far suggests the possibly of the huge landslide offshore the lagoon and tsunami energy concentration at the terrace topography in front of the Sissano lagoon.

(5) The regional mitigation meeting proposes some relocation system of the survivors villages and future warning system along the PNG coastline.

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List of Symbols

D : $=h+\eta$

f : coefficient for energy ross on sea bed

g : gravity acceleration
H : tsunami height
h : water depth
M : energy flux on x-direction
N : energy flux on y-direction
t : time
x : spatial coordinate on water surface
y : spatial coordinate on water surface
η : water elevation
μ : tsunami flow velocity
ρ : spatial density of green belt