

COASTAL DESIGN AND TSUNAMI MITIGATION FOR SHELTER/HOUSE RECONSTRUCTION ON THE WEST COAST ACEH

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ABSTRACT: The author was commissioned by RedR Australia to work with UNHCR to investigate and report on the provision of coastal design and tsunami mitigation requirements for planning of a program of shelter/house reconstruction along the west coast of Aceh Province. Inspections by land and air of a number of settlements and town sites along the west coast of Aceh were made and discussions were held with survivors who had witnessed the progress of the tsunami across the coastline and over the land. A summary of these observations are presented together with conclusions regarding the wave height, run-up, inundation and the effect these waves had on a variety of structures including houses, roads and bridges. A simple numerical model, calibrated against the field observations, was used to estimate the water velocities and forces that occurred. The problems of warning systems and escape options are addressed together with the probability of reoccurrence of similar tsunamis. This information was used to develop guidelines for planning and construction of housing and villages, the provision of safe areas, and the reconstruction of infrastructure and roads.

1. INTRODUCTION

The Sumatra–Andaman Islands earthquake of magnitude 9.0 that occurred on Sunday 26 December 2004 at 0058 UTC at a point (3.30N, 95.78S) 250 km south of Banda Aceh was the largest earthquake since the magnitude 9.2 Alaskan earthquake of 1964, and was among the five largest earthquakes in the past century. The earthquake triggered a massive tsunami that caused extreme inundation and destruction in the northern Indian Ocean and resulted in massive loss of life and damage to the west and north-east coast of Aceh Province in the Republic of Indonesia.

During February/March and July/August 2005, the author as member of the RedR Australia support team assisted UNHCR in developing coastal design and tsunami mitigation guidelines for their shelter/house reconstruction program at selected sites along the west coast of Aceh. The investigation involved reviewing the tsunami events in the area, inspecting eight sites along 200 km. of the west coast between Banda Aceh and south of Meulaboh, speaking to eyewitnesses, assessing the wave height and the resultant damage at each site, undertaking simple numerical modeling and assessing planning options, warning systems and Government proposals.

2. EARTHQUAKE AND TSUNAMI

The fault zone that runs to the west of Sumatra is one of the more active fault zones. Numerous earthquakes have occurred in that area and many have produced tsunamis in the past. The 26 December 2004 earthquake resulted in a fault rupture zone, uplifted by several metres, and covering an area 150 km. wide that extended 1300 km. to the Andaman Island, (see Fig. 1)[1]. Following the earthquake, HMS Scott a British Navy Hydrographical Survey Vessel, undertook a survey of the seabed west of Aceh. Figure 2[2] is from a presentation of this survey and shows the positions of the epicentre (yellow dot), the area of maximum seabed movement (red dot) 280 km south-southeast of Banda Aceh. This survey also showed up many landslides and slips occurred in the trench to the north of the epicentre and area of maximum seabed movement.

From the field observations and discussions with eyewitnesses, it was estimated that the height of the tsunami wave at the coastline was 9 to 10 metres at Banda Aceh, about 13 metres at Lhoknga, about 10 metres at Calang

and < 5 metres at Meulaboh. The tsunami height along the entire coast between Banda Aceh and Calang (100 km.), was in excess of 10 metres while the run-up was up to 35 metres at Lhoknga.



Fig. 1 Earthquake Rupture Zone.

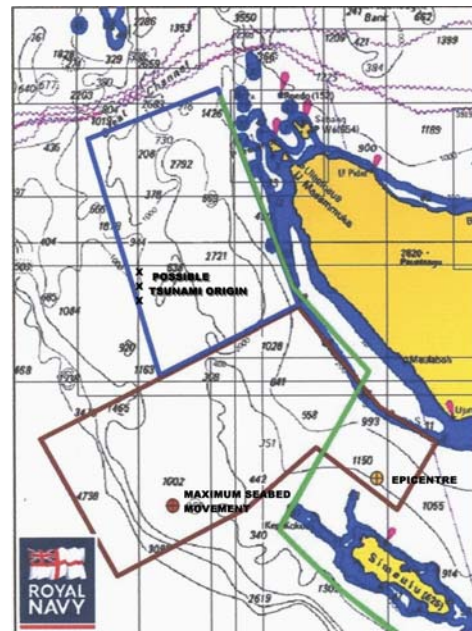


Fig. 2 HMS Scott Hydrographical Survey

Eyewitnesses advised that the earthquake lasted 15 minutes and that the time interval from the start of the earthquake to the arrival of the first wave front of the tsunami was about 35 minutes at Banda Aceh, 25 minutes at Calang and 50 minutes at Meulaboh. The source of the tsunami is unclear at present. However, based on triangulation from the above arrival times for the first wave, a possible source is an area west of Calang as shown on Figure 2. This is near the area of landslides and slips reported in the trench north of the epicentre by HMS Scott.

3. FIELD OBSERVATIONS

In all the areas inspected, the tsunami completely removed all the existing housing from the first 500 metres from the foreshore. In most areas inspected up to 150 metres of coast was lost to the sea and there was significant settlement of coastal land. Generally, settlements were in the ranges of 0.5 to 1 metres however, the maximum observed settlement of about 2 metres was in an area south of Meulaboh. This coastal destruction occurred even when there was a large difference in the tsunami wave height such as at Banda Aceh and at Meulaboh where the wave height was about 10 metres and less than 5 metres respectively. A few well-engineered and constructed buildings such as mosques survived at the foreshore but these are the exceptions.



Fig. 3a Banda Aceh Uleele Before Tsunami



Fig. 3b Banda Aceh Uleele After Tsunami

At Uleele, a coastal suburb of Banda Aceh, the 10-metre high tsunami resulted in complete foreshore destruction and extensive coastal erosion and destroyed the port (see Fig. 3a and 3b). The housing at Uleele was expensive two or more storey brick construction constructed on a coastal spit and it was destroyed (see Fig. 4). However, adjacent to this area of destruction, a mosque survived the tsunami wave with minor earthquake damage to the upper floor awning and minor tsunami damage to the roof (see Fig 5). This indicated that the tsunami wave was 6 to 7 metres above the ground level (approximately 8 to 9 metres above sea level).



Fig. 4 Foreshore at Uleele, Banda Aceh



Fig. 5 Mosque at Uleele, Banda Aceh

The tsunami generated considerable amount of debris, which was carried along by the wave. This debris magnified the forces and the death toll and destruction was greater as the wave moved inland. Virtually all the housing was destroyed in the first 2 kilometres from the coast and it was not until the wave was about 3.5 km inland that the velocities slowed sufficiently not to destroy most brick houses. Almost all timber housing to the edge of the inundation, (4.5 kilometres from the coast) were destroyed.

Just about every mosque along the west coast survived the tsunami with minimal damage. It is believed this occurred for two reasons. Firstly, the structures are more open than the normal house and are subjected to lesser wave forces and secondly mosques are built to a higher standard of design and construction than housing and the correct quantity of steel and cement was used in the reinforced concrete construction. This would suggest that structures properly designed and constructed in accordance with the Indonesian Building Code have a very good chance of surviving a tsunami and providing safe refuges.

At Lhohnga, 10 km west of Banda Aceh the area was completely devastated by a wave of over 13 metres height, as estimated from stripped bark on trees. The run-up against the coastal hills near the cement plant was 35 metres[3]as measured from the trim line. All the housing that was on lower ground and within 6 km of the coast was demolished. The only remaining structures at Lhohnga were the mosque and the cement plant. At the cement plant harbour a 100-metre ship was capsized at the berth and the head of the tetrapod armour breakwater failed. The trim line where vegetation was stripped from the hills is seen in Fig. 6. Generally run-ups, as measured by the trim line were 10 to 15 metres 1 km from the foreshore. At 2 km from the shoreline, the trim line while still observable was reduced to < 5 metres.



Fig. 6 Lhoknga Cement Plant, Breakwater, Wharf, and Capsized Ship



Fig. 7 Calang Peninsular

Calang, a district capital 100 km from Banda Aceh, is built on a peninsular on low-lying ground. The peninsular has three hills spaced such that the tsunami approached the town from three directions (see Fig. 7). This resulted in amplification of the water level in areas where the wave fronts met resulting in maximum wave run-up of up to 25 metres, as observed from the trim line. In many areas, the trim line was in excess of 20 metres

Eyewitness advised that about 10 minutes after the earthquake had ended the water retreated from the shore and people on motor bikes drove round the town yelling that the big wave was coming and telling people to escape to the hills. With in five minutes water started to enter the road at the base of the hills while residents were running to escape the wave. However, the line of houses at the base of the hill stopped access directly to the hill and the one road was the only way up the hill to safety. The road was full of people, there was a traffic jam of people, bikes, and cars and most people were not able to reach safety including some that lived only 100 metres from the point where the road started ascending the hill. Official figures show that 90% of the population of 9,000 lost their lives in the tsunami. The people of Calang were aware of the danger of the tsunami but the lack of town planning controls resulted in shops and housing being built so that the direct access to the safety of the hills was blocked.



Fig. 8: Meulaboh Peninsular - Total destruction except for the Army headquarters

At Meulaboh, where the height of the tsunami wave was less than 5 metres, the penetration was about 2 km. with most brick buildings beyond 1.5 km. surviving with minimal damage. Considerable damage occurred in the first kilometre including destruction of the bridge and the nearly complete destruction of the army barracks on the peninsular (see Fig. 8). The only buildings remaining were the Headquarters Building and the Communication Building. Both these buildings were well-designed and constructed buildings.

The tsunami destroyed the west coast main road for most of its length. It was too close to the coast (foreduced to 1.5 km inland) and too low to withstand the tsunami wave forces. This road was the main transport link along the west coast and with its destruction the capacity to undertake the reconstruction is greatly restricted. The wave and the debris destroyed nearly all the truss bridges along the road

4. NUMERICAL MODELING

In order to estimate the wave velocities and forces that could be encountered from a 10-metre tsunami as it moved inland a simple two-dimensional numerical modeling study was undertaken. The study assumed that the land inshore from the coast was level, was 1 metre above sea level and the offshore seabed slope was 1:100. The model was calibrated against the observed tsunami wave heights that were measured in the field. This required adjustment of the model bed friction as buildings and trees were demolished with the progress of the wave. The model results obtained included water velocities and wave heights as the wave moved inland and the wave run-up for hills at 500 metre, 1 km., and 2 km. from the coastline.

The significant feature of the tsunami, as described by the eyewitnesses, is that it came as several, between three and five, broken wave fronts each higher than the previous one. The number of wave fronts appeared to be a function of the Tsunami height and the seabed slope. Eyewitnesses said that the first wave was slower and in some cases smaller and the impact wave was the second or third wave front. In this simple numerical model, there are no broken wave fronts and the impact or first wave is very steep and has the highest velocities. Despite this significant difference, it is considered that the model gives a reasonable representation for design purposes of the actual impact wave and velocities.

The results of modeling and field observations are at Fig. 9 for wave heights, Fig. 10 for water velocities, Table 1 for run-up and Table 2 for wave heights and velocities,. In most cases, the impact wave will cause the more severe design loading condition for one and two story housing, buildings, and structures while the maximum wave will be the design condition for larger buildings and structures. It is also the most important design criteria for defining safe areas.

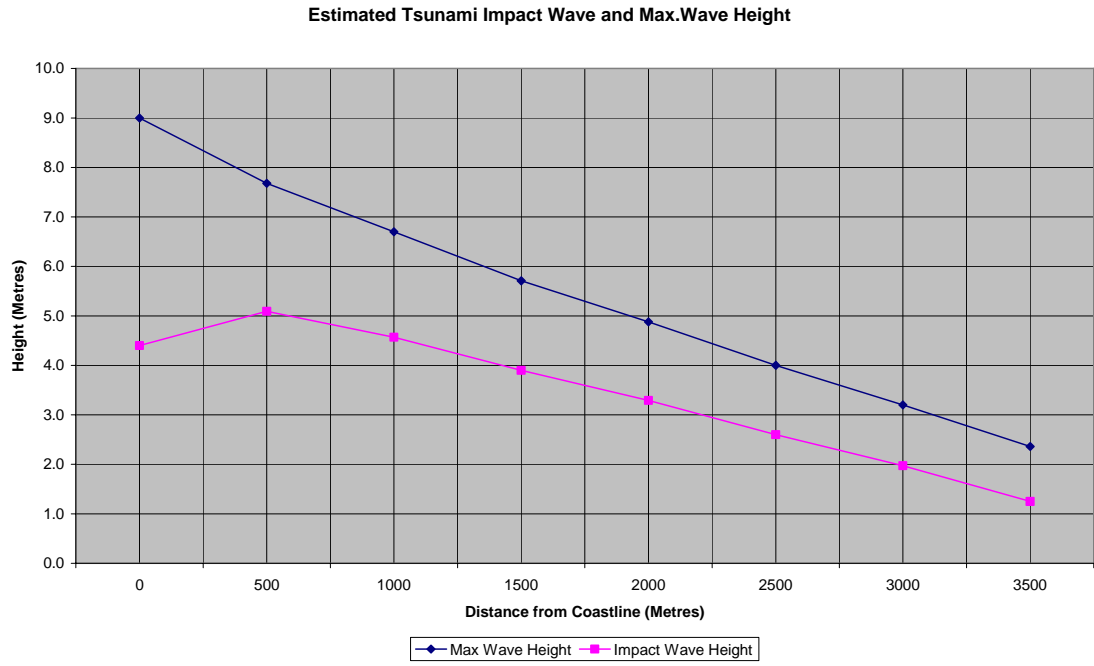


Fig. 9: Estimated Wave Heights for the Impact Wave and the Maximum Wave

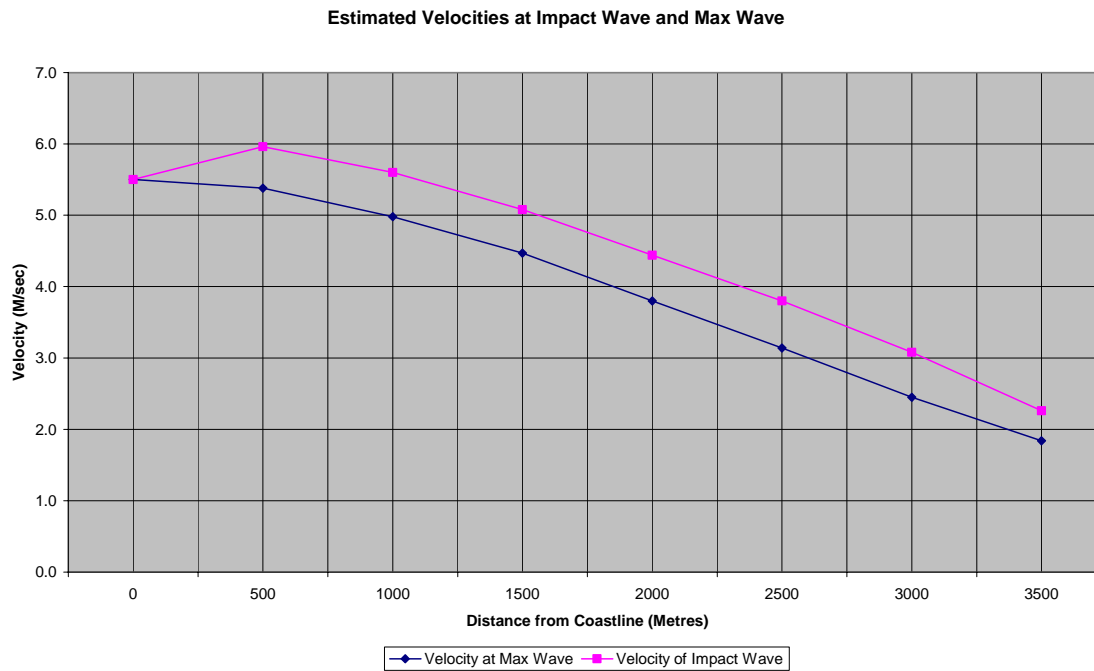


Fig. 10: Estimated Water Velocities for the Impact Wave and the Maximum Wave

Table 1: Tsunami Wave Run-Up Levels for 10 m Tsunami at Coastline

Distance from Coast	Calculated Run -Up	Observed Trim Line
500 m	18 m	20 m
1 km	14 m	15 m
2 km	10 m	<5 m
3 km	6 m	

The difference between the observed trim line and calculated run-up can be explained by the fact the velocities at 2 km inland are too low to strip the vegetation from the hills. It is believed that velocities in excess of 4.5 m/sec are required to strip the vegetation. The calculate run-up should be used to determine the elevation for safe areas on hills.

Table 2: Estimated Wave Heights and Velocities for 10 metre Tsunami at Coastline

Distance from Shoreline (Metres)	Impact or Front Wave		Maximum Wave	
	Wave Height (Metres)	Water Velocity* (M/Sec)	Wave Height (Metres)	Water Velocity* (M/Sec)
At shoreline	4.5	5.5	10.0	5.5
500	5.0	6.0	8.0	5.5
1000	4.5	5.5	7.0	5.0
1500	4.0	5.0	6.0	4.5
2000	3.5	4.5	5.0	4.0
2500	2.5	4.0	4.0	3.0
3000	2.0	3.0	3.0	2.5
3500	1.0	2.0	2.5	2.0

**The forces determined from these velocities should be doubled to allow for debris loading.*

5. PROBABILITY OF OCCURRENCE OF TSUNAMIS

The Earthquake Research Institute of the University of Tokyo has published a diagram on its web site that showed that in the immediate area of Sumatra there have been seven earthquakes in the last 170 years that have triggered tsunamis. The earthquakes noted are 1833 (M9), 1861 (M8.5), 1907, 1935 (M7.7) and 2004 (M9.3) west of Aceh and 1881 (M7.9) and 1941 (M7.7) in the Andaman Islands north of Banda Aceh and west of Phuket in Thailand. Between 1833 and 1941, six tsunamis occurred at an average of one each 22 years

Dr Phil Cummins of Geosciences Australia in a article[4] on the 1833 earthquake noted that this earthquake produced a tsunami of a similar size to the 26th December tsunami along the west coast of Sumatra. A more recent news item quotes Dr Cummins[5] saying, “another earthquake in the area of the 1833 disaster could happen again within 20 to 50 years, due to 170 years of built-up stress. It is possible that it will happen again in the rupture area of the 1833 earthquake. Roughly 200 years is about the amount of time expected for the strain energy to accumulate enough to cause another earthquake”. He argues that the 2004 earthquake has relieved the stresses in the zone in northern Sumatra but it has not relieved the stresses in the region of the 1833 earthquake. Like the 1833 earthquake, a future earthquake will cause a massive tsunami that will devastate the west coast of Sumatra. If this tsunami is a similar size to the 1833 and 2004 tsunamis it is probable that areas south of Meulaboh could be hit by a 10 metre or higher tsunami while Banda Aceh might receive a 5-metre tsunami.

In effect, major tsunami causing earthquakes occur about every 200 years at different sections of the fault zone west of Sumatra and they are out of phase by about 40 years. Hence, the average return period of a disastrous tsunami is of the order of 100 years but the present probability of a it occurring now is 3% per annum based on it occurring in the next 20 to 50 years. Also, the average occurrence of smaller tsunamis (less than 5 metres) over the last 170 years is about 30 years and it is likely these events will continue to occur.

These frequencies well within the time frame for determining design forces for important buildings and should be of major importance for the design of future planning and construction. However and more importantly these frequencies are of major concern because it is within the lifetime of the people living in the area and moving back into their devastated housing sites. Governments must recognise that there will be a massive loss of life again if action is not taken to have people living in safe areas.

6. WARNING SYSTEMS AND SAFE EVACUATION PLANS

For areas close to the fault zone such as west Aceh, it is unlikely that the planned Indian Ocean tsunami warning system can respond quickly enough to save lives. From the end of the earthquake, it was only 5 minutes before the first indication (the withdrawal of the water from the shore) of the tsunami was observed at Calang. This time was insufficient and 90% of the population died. This highlights how little time is available for warnings to be given to areas that are closest to the tsunami origin.

The planning must assume virtually no warning of any future tsunami and plans should be based on reacting immediately to significant earthquakes. Many survivors stated that it was not possible to move far during the earthquake and that they could only run after the earthquake finished. In Calang there was only 10 minutes between the earthquake stopping and the first wave arriving. It should be noted that what happened at Calang could happen to any point along the West Sumatran coast that is close to an earthquake epicentre. There is a need for people living in low exposed areas to be very aware of tsunamis and the need to move to safe areas, such as hills or safe buildings at the commencement of significant earthquakes. Smaller earthquakes can trigger an underwater landslip and start a tsunami. Access to these safe areas needs to allow for rapid movement, possibility at night of a large number of people in a very short time. Access to safe refuges should take no longer than 10 minutes (150 to 200 metres to allow for the elderly and young children at night) to reach safety.

To achieve this there is a need to develop a tsunami escape plan that is kept up to date, and includes a continuous education and media program. While the recent events are currently clear in everyone's mind, this attention will diminish with time, and the required attention for planning to escape may be inadequate. Failure to plan and inform people about the tsunami hazard and what actions they should take will result in disasters in the future. This should include regular practice evacuations to test the procedures.

7. POSSIBLE OPTIONS FOR RECONSTRUCTION

Any plan for the reconstruction should follow the seven principles that are described in US Government National Tsunami Hazard Mitigation Program[6]. The possibility of major rare destructive events occurring creates a dilemma in the planning for the future redevelopment, as there is always a wish of property owners to return to their place of residence, despite the risks that may be involved. There is a conflict between getting people back to their home and establishing their lives and the longer term planning that takes account of the real risks and may require people to move to safer areas.

For areas close to the earthquake and tsunami trigger there does not appear to be any reliable warning system that a tsunami is approaching apart from moving immediately the earthquake starts. In these circumstances, the only reliable method of saving life and property is to build residential housing in areas that are safe because of their height and strength or distance inland. However, this was not practical in the short term and immediate action was necessary to allow people to move out of tents into more livable and healthy accommodation.

Safe areas could be areas greater than 4.5 km inland, hills satisfying the hill height criteria Table 3 or buildings such as school or public buildings that have adequate areas above the levels also listed in Table 3 and has been designed to withstand the expected wave forces. The bottom levels of these safe buildings could be used but it would be expected that walls and contents would be destroyed in the event of a large tsunami and debris-creating materials should be limited in their use. .

Table 3: Estimated Safe Heights for Hills and Clearance Heights for Buildings

	Height above Ground Level (m)			
	500m inland	1000m inland	2000m inland	3000m inland
Safe Height for Hills	22	17	10	6
Building Clearance Height Required	10	9	6.5	4

8. STUDY RECOMMENDATIONS

In the report to UNHCR, the Author made the following generic recommendations: They are generic as there is insufficient topographical data on land levels to predict site-specific wave heights and water velocities as the tsunami wave travels inland. The best maps available showed 25 metre contours only.

- Establish a Tsunami Warning System in the Indian Ocean with special attention to the needs of the west coast of Sumatra.
- Develop a sound, well-understood evacuation program updated on a regular basis for the west coast of Sumatra. The trigger for an evacuation must be the earthquake itself.
- A 10-metre high tsunami with a return period of the order of 100 years should be the design tsunami for tsunami planning on the whole west coast of Aceh.
- The primary approach for protection of people should be to build general housing in areas that are outside the design tsunami inundation zone.
- No housing development be constructed in the first 500 metres from high tide mark on the foreshore or coastal lagoon. Allowable activities within that zone could include shipping and port activities; fishing and aquaculture
- Development inland from the initial 500 metres from the foreshore should be either open space or well-engineered, non debris creating buildings, that can withstand the tsunami wave forces to Building Centre of Japan - Structural Design Method of Buildings for Tsunami Resistance (Proposed)[7]. The buildings should provide a safe refuge with heights in excess of the clearance levels listed at Table 3.
- Normal reinforced concrete framed brick or reinforced concrete block housing will not withstand wave heights greater than 2.5 metres.
- Buildings/housing on low flat areas and not satisfying the height criteria in Table 4 require places of safe refuge accessible within 10 minutes (150 to 200 metres to allow for the elderly and young children at night).
- Hills require regular wide pedestrian access easements with safe paths and steps to a safe height.
- In remote areas where there are high hills immediately behind the foreshore (up to 1 km,) housing developments should not be supported unless it can be shown there is a warning system that will be adequate in an emergency and allow people to reach safe refuges.
- Hospitals should not be used as safe refuges. They should be built in areas not subject to inundation so that they are immediately available with medical support when another tsunami disaster occurs.
- The reconstructed west coast main road should be built inland of the inundation areas, approximately 5 km in the flat areas and above 25 metres in hilly areas near the coast, to provide an all conditions transport link in times of emergency and draw ribbon housing development away from the coast.

9. INDONESIAN GOVERNMENT POLICY

The Indonesian Government in March 2005 issued a Master Plan for Rehabilitation and Reconstruction report. This is a very extensive document and covered all areas of reconstruction. The plan proposed construction of a buffer zone (green belt) similar to the 500 metre exclusion zone noted above. They also proposed graduated building further inland from the green zone. These recommendations were discussed with the people in Aceh. The reception was extremely negative and the Government reviewed its approach to the rehabilitation and reconstruction.

It is understood that the policy now allows people to rebuild in all areas. However, government will commence an education program to allow people to understand the risks and the opportunities available to reduce the risks. The people will then be given 10 years to decide whether they want to move to safer areas. This timing allows the Government to obtain land that is not presently available. In some cases the District Capitals such as Calang will be moved inland clear of any inundation.

USAID are undertaking studies for the construction of a new coast road and they propose to fund it. This road will be generally 4 km to 5 km inland. The exact alignment is awaiting Government purchase of the land. It is expected that the ribbon development that existed along the old coast road and was dependent on cottage industries based on coconut and palm plantations will move to the new road. This is because the plantations have been destroyed and the market is mainly passing main road traffic based.

10. ACKNOWLEDGEMENT

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