

3. SURVEY RESULTS ON TSUNAMI DAMAGE AND TRACE HEIGHT

3.1 Male'

Male' Island is protected by the solid seawalls because Male' city is the capital of the Maldives and the reef had been reclaimed completely. The Indian Ocean tsunami exceeded the seawall and inundated Male'; however, the island was not sunk below the water surface by the tsunami. This tsunami caused some damages in Male'; (1) several ships were carried and remained on the quay, (2) a part of sheet-pile quaywall in the north wharf was jugged out over the port. However, those damages were not so severe and recovered quickly. The proper measures were enforced by the Maldives' government after the disaster, although those were enabled by the fact that Male' kept in the normal situation. If Male' island became inhabitable or the port facilities were destroyed severely, the influences on the Maldives' society were immeasurable both economically and mentally. In this sense, the tsunami event occurred in Male' should be investigated carefully.

Figure 3.1.1 shows the tide record at Male', where the sea surface elevation from the mean sea level (M.S.L.) is drawn in centimeter. This figure suggests that the sea level at the tsunami arrival was almost the same as the M.S.L., -5~6cm, and the maximum tsunami height was approximately 1.45m. Note that the tide gage is installed in the atoll side, thus this tsunami height is that in the north side of Male'.

The representative of the crown height of seawall is 1.96m in the west coast, 1.36m in the north coast, 2.16m in the east coast, and 1.46 to 3.36m in the south coast from the M.S.L., although the crown height is partially higher. The representative crown height of quaywall is 1.16m in the north and south wharf. Thus, the tsunami might overflow the quaywall in the north and south wharf. It is possible that the tsunami height in the south and east coast is slightly different from the tide record, because the east and south coast of Male' faces the out of atoll. The atolls might be a kind of obstacle for the tsunami, so the tsunami flow probably concentrated in the channel between the atolls. Thus the tsunami height in the south coast was probably amplified slightly. The tsunami height in the east coast, also, may be amplified because the tsunami was dammed by Male' Island in the east coast.

Because Male' Island was not submerged below the tsunami as stated above, the trace height in Male' does not agree with the tsunami height. Thus, the inundation height in Male' has no importance in the scientific meaning. However, the inundation area of Male' is important in the engineering meaning, thus that was examined in our survey.

The boundary of inundation and non-inundation area was determined at every street

by the eyewitness evidences of the residents. Figure 3.1.2 shows the measured result of the inundation area in Male' Island. The inside of the blue line in the figure was not inundated, and the inundation area is approximately 60% of the island. The ground elevation of the boundary of inundation is approximately 1.1m almost over the island. This fact may indicate that the total volume of the overflowed seawater reached the 1.1m-line when the seawater was stored in the seawalls like a reservoir. On the other hand, the ground elevation of inundation-boundary in a part of north coast and a part of east coast is higher than 1.1m. In this region, the overflowed water might have some inertia force, and reached the high ground temporally.

Because the tsunami height was higher than the crown height of quaywall, it is thought that the inundated seawater mainly entered over the quaywall in the north and south wharf. However, Figure 3.1.2 shows that the overtopping over the seawall at the east coast was not negligible. The tsunami height, perhaps, was amplified in the east coast because the tsunami was dammed by the island there; and it made the overtopping of the swell and wind wave over the seawall easy.

Figure 3.1.3 shows the comparison of the inundation area and the reclamation area in Male' Island. The blue line denotes the inundation boundary, and the black line the shape of the original Male' Island. This figure indicates that the reclamation land was fully inundated by the tsunami, and the inundation area was very similar to the reclamation area. Note that the reclamation land is relatively danger in comparison to the original land if the protection level (e.g. crown height of seawall) is the same.

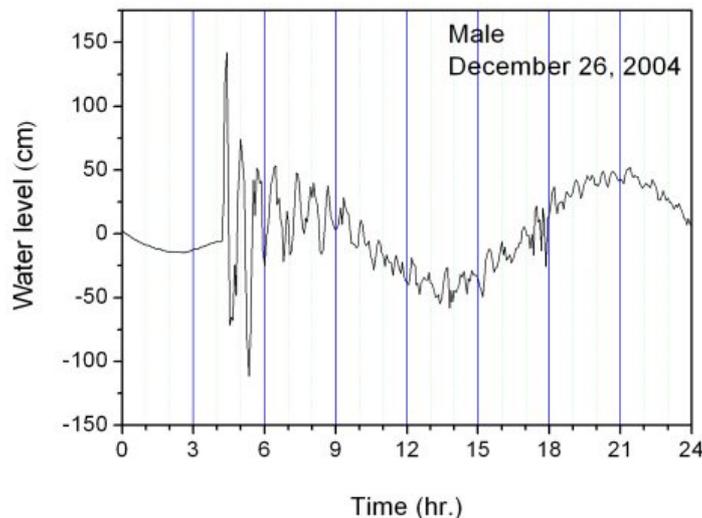


Figure 3.1.1 Tide record at Male' (time in UTC, tide level in centimeter from M.S.L., measured and provided by Sea Level Center, University of Hawaii)

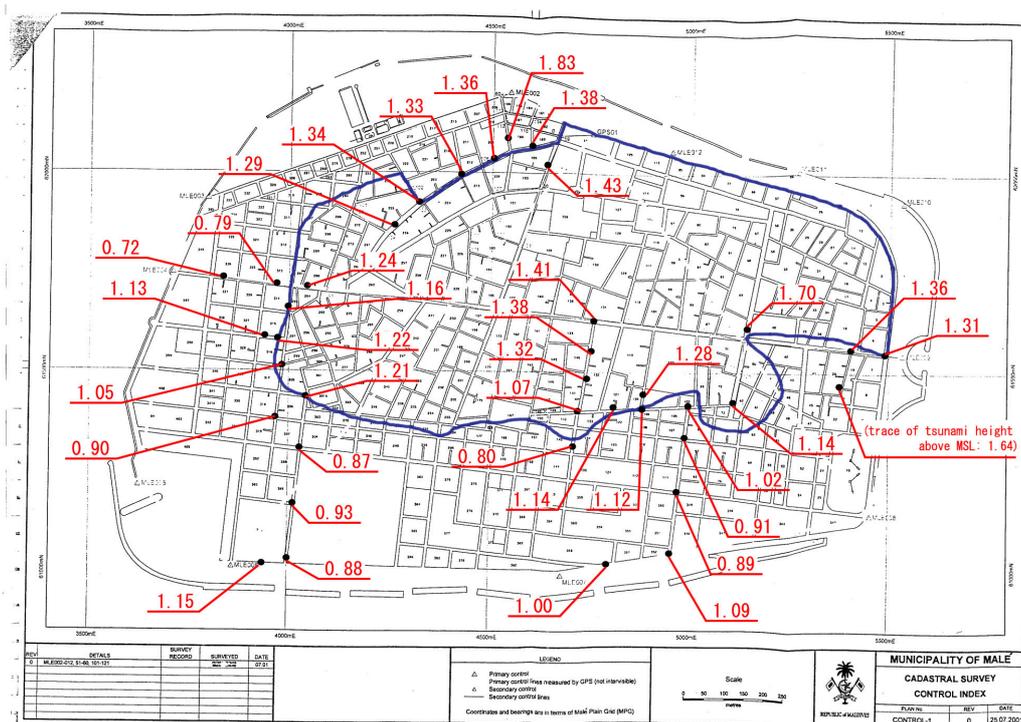


Figure 3.1.2 Inundation area in Male' and the ground elevation near the boundary of inundation

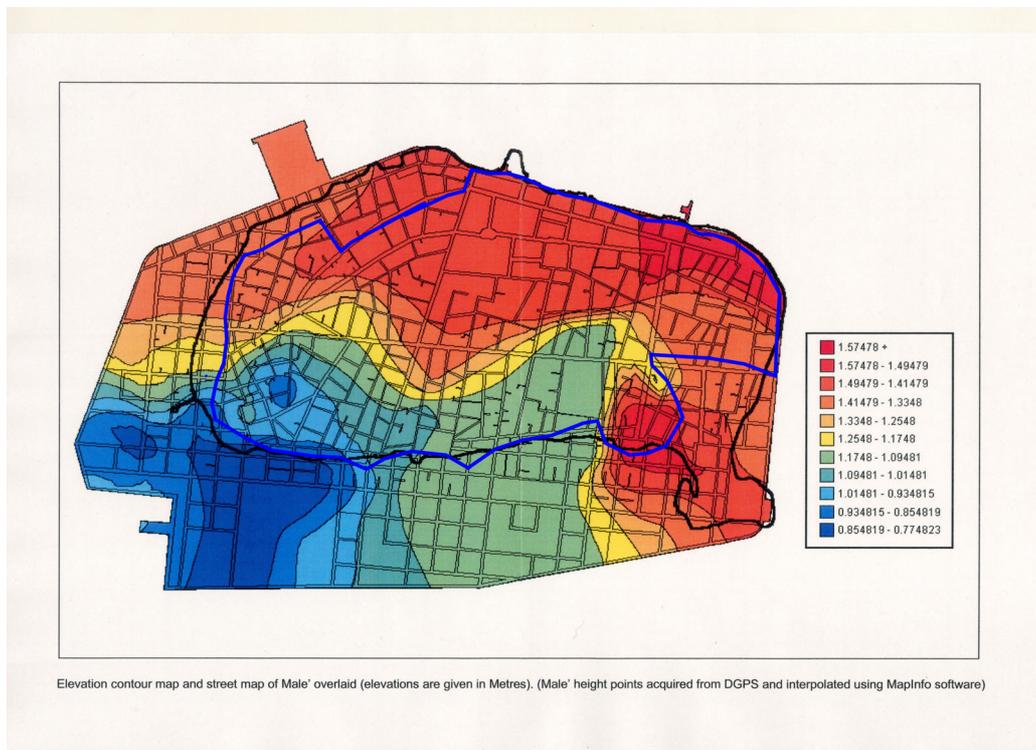


Figure 3.1.3 Comparison of the inundation area (blue line) and the shape of the original island (black line)

3.2 Male' International Airport (Hulhule) and Hulhumale'

3.2.1 Introduction

Male' International Airport is situated on the Hulhule Island, which is on the eastern rim of Male' Atoll, as shown in Figure 3.2.1. The location is roughly at 4°11'29"N and 73°31'45"E. The Hulhule Island is a long and narrow island in the north-south direction. The tsunami came from the east. In the northeast direction of the airport island there is a new reclaimed island, Hulhumale', and a causeway connects these islands. Many apartments exist already in the Hulhumale'.

The height of the airport island is about 1.7m above the mean sea level and less than 1m locally in the west side area. In the low-lying area, high waves overtopped sometimes before the tsunami. The airport facilities were protected by seawalls whose heights varied from M.S.L.+2.0m to M.S.L.+2.7m in the areas facing to the open sea especially.

According to the investigation of the Maldives Airports Co. Ltd., two-thirds of the airport island was flooded, and the runway was out of operation for approximately 10 hours, resulting from debris and detritus due to the tsunami flooding. The runway lights were repaired after 18 hours. Photo 3.2.1 shows the inundated airport by the tsunami. The runway was flooded and coral sand flowed out of the island.

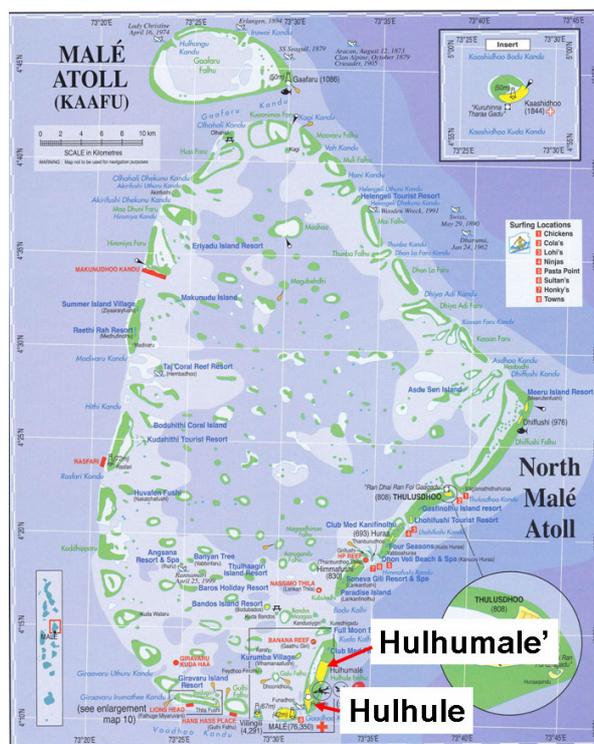


Figure 3.2.1 Male' Atoll and Hulhule Island (The based map is from Atlas of the Maldives, 2004, ©Atoll Editions.)



Photo 3.2.1 Male' International Airport inundated by the tsunami. ©Mr. Todd Rempel

3.2.2 Tsunami Trace Height

A summary of the measured tsunami trace heights is shown in Figure 3.2.2. The height of the tsunami attacking the airport was more than 2m approximately. At Points 7, 8 and 9 in the bottom of the inner sea area between the causeway and the airport, there were high records. According to tsunami observers at Points 8 and 9, three tsunamis attacked and the first tsunami came from the east direction around 9:20 in local time. The second tsunami came a few minutes later after the first tsunami came and it was the biggest among all of the tsunami waves. Since the high tsunami trace heights were found around the bottom of the inner sea area, it seems that the second tsunami came through the inner sea from the north direction and it lost the places to go there. However, if the second tsunami passed in the north of Hulhumale' and changed the propagation direction into the inner sea area by the west reef edge, the time interval between the first tsunami and second tsunami is about 12 minutes, in which the inner sea area is assumed to be 5km long and 5m deep. If the second tsunami came from the west of the Airport Island, the propagation time is almost the same. These time intervals are different from the hearing results. Therefore, the tsunami in the bottom of the inner sea area was probably affected by local topography change and existence of structures. To clarify the characteristics of the high tsunami, we need a more detailed numerical simulation on the tsunami.

On the other hand, in Figure 3.1.1 in the previous section, the tide record at the Male' tide station shows that the time interval between the first tsunami and second tsunami is about 40 minutes. The second tsunami in the tide record in the west of the airport island is different from the second tsunami in the inner sea. In the south of Sri Lanka, three tsunamis were observed, and the multiple tsunamis around Male' were the same as the tsunamis in Sri Lanka.

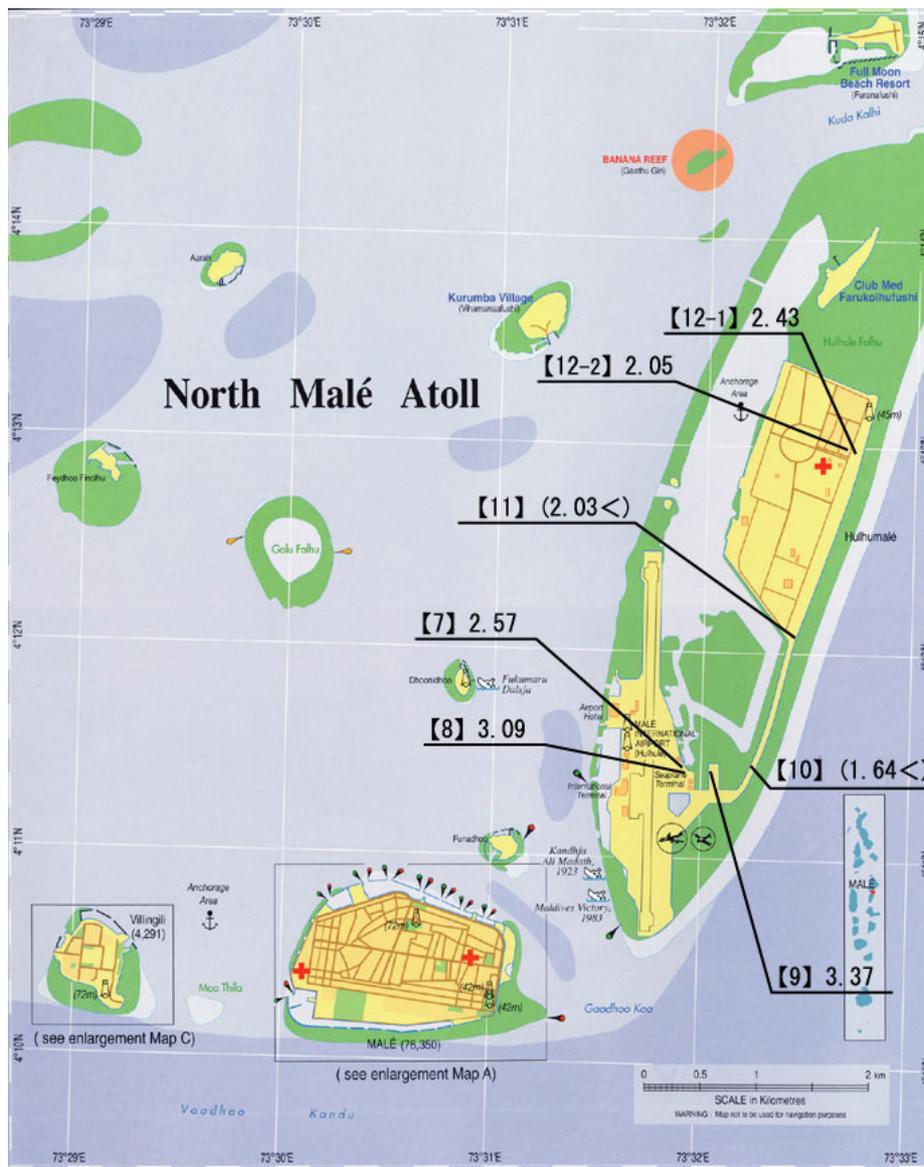


Figure 3.2.2 Tsunami trace heights

3.2.3 Tsunami Damage on Structures

Figure 3.2.3 shows some structural damages due to the tsunami. The most severe damages are along the inner sea between the causeway and airport.

In Hulhumalé, the shore protection works which consisted of cement bags were partially damaged as shown in Photo 3.2.2. Although the tsunami flow washed some cement bags on the land about 15m apart from the coast, it seems that they were mainly destroyed by the backwash of the tsunami, judging from the feature of the scattered bags on the beach.

The east and west sides of the causeway were eroded by the tsunami action as shown in Photo 3.2.3. Tsunami pressure also broke an on-land wall even behind coastal

houses as shown in Photo 3.2.4. Seawalls were damaged in some areas as shown in Photo 3.2.5, and especially in the east side of the airport along the inner sea area the seawall were collapsed as shown in Photo 3.2.6 by the high tsunami. The seawall which was made from coral stones covered by concrete suffered severe damage from the tsunami action. In the southwest side of the airport, parapets of the seawall were fallen down as shown in Photo 3.2.7. Since the south and southwest sides of the airport faces the open sea, high tsunami attacks there.

The tsunami forces acting on vertical walls can be evaluated the following empirical equation.

$$p = 2.2\rho g a_1$$

in which p : tsunami pressure (kN/m^2), ρ : water density (t/m^3), g : gravitational acceleration (m/s^2) and a_1 : tsunami height (m). The tsunami height here is not the wave height of tsunami, and corresponds to the wave amplitude. For tsunami bores, it is the bore height. Using the equation, in the case of the tsunami of 2m high, the tsunami pressure is 44kN/m^2 , or 4.5tf/m^2 .

3.2.4 Another Tsunami Feature

There is an interesting comment from an observer of the tsunami. It is that the water surface bubbled in a waterway of the inner sea area and cream-colored water was extended around 8:45 before the first tsunami arrival. This may be caused by the tsunami pressure in the phase of the increasing water surface before the maximum water elevation of the first tsunami. The pressure was transmitted in the coral sea bottom in which there are some water paths, and it made coral sand spring from the sea bottom.

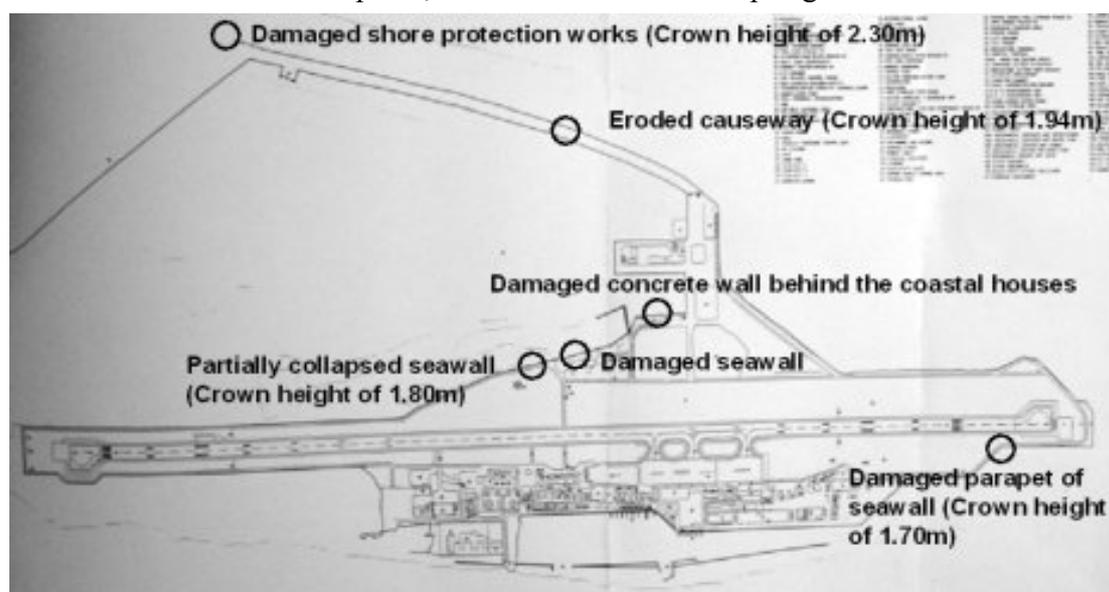


Figure 3.2.3 Tsunami damages



Photo 3.2.2 Damaged shore protection works



Photo 3.2.3 Eroded causeway



Photo 3.2.4 Damaged inland wall



Photo 3.2.5 Damaged seawall



Photo 3.2.6 Collapsed seawall



Photo 3.2.7 Damaged parapet of seawall

3.3 Haa Dhaalu Atoll

In Is. Hanimaadhoo of Haa Dhaalu Atoll (see Figure 3.3.1), height of the tsunami should have reached 1.7 m above the sea level, approximately. In this island, UHSLC has been collecting the data of sea level changes, and the record shows the abnormal fluctuations (Figure 3.3.2).

We selected this island as one of our survey sites, because there is an airport and plays principal roles in the northern part of the Maldives. The survey started on February 3, 2005. In addition to Is. Hanimaadhoo, Is. Kulhudhuffushi (Photo 3.3.1, Figure 3.3.3) is also surveyed. In this survey, we tried to determine the trace heights of tsunami by asking the residents, or by finding marks of tsunami on the walls and houses, and measured them.

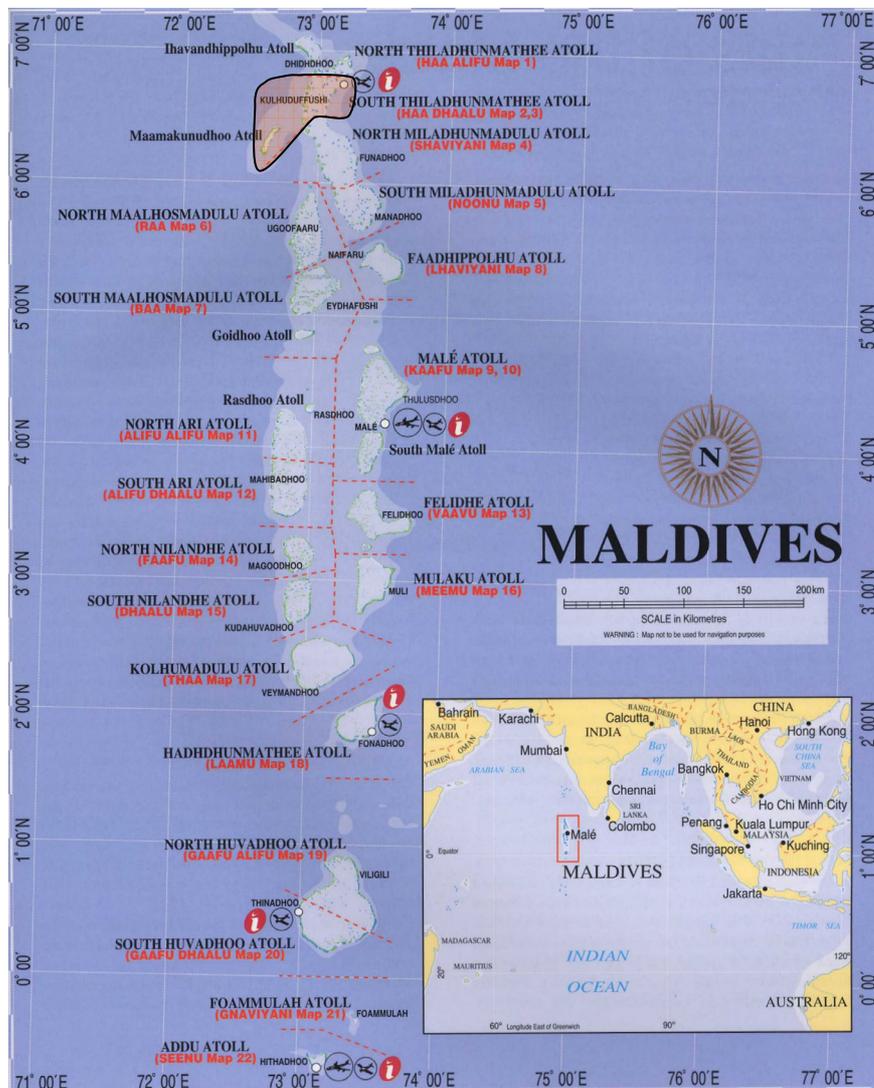
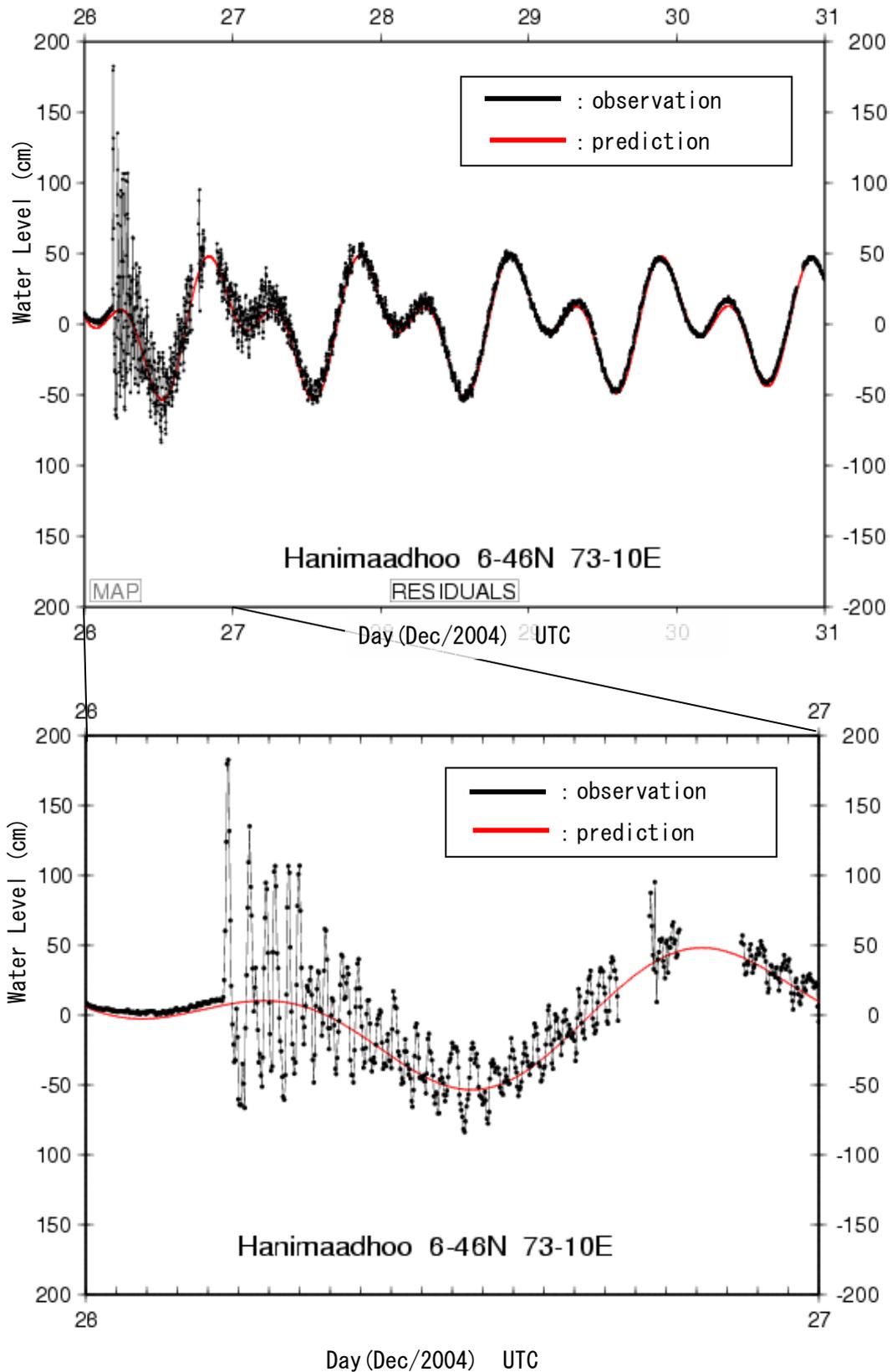


Figure 3.3.1 Location Map of Haa Dhaalu Atoll (Based map is from Atlas of the Maldives, 2004, ©Atoll Editions.)



Reference : <http://ilikai.soest.hawaii.edu/uhscl/iotd/> modified by H. FUJII
 Figure 3.3.2 Tide record at Hanimaadhoo(time in UTC, tide level in centimeter from M.S.L., measured and provided by Sea Level Center University of Hawaii)

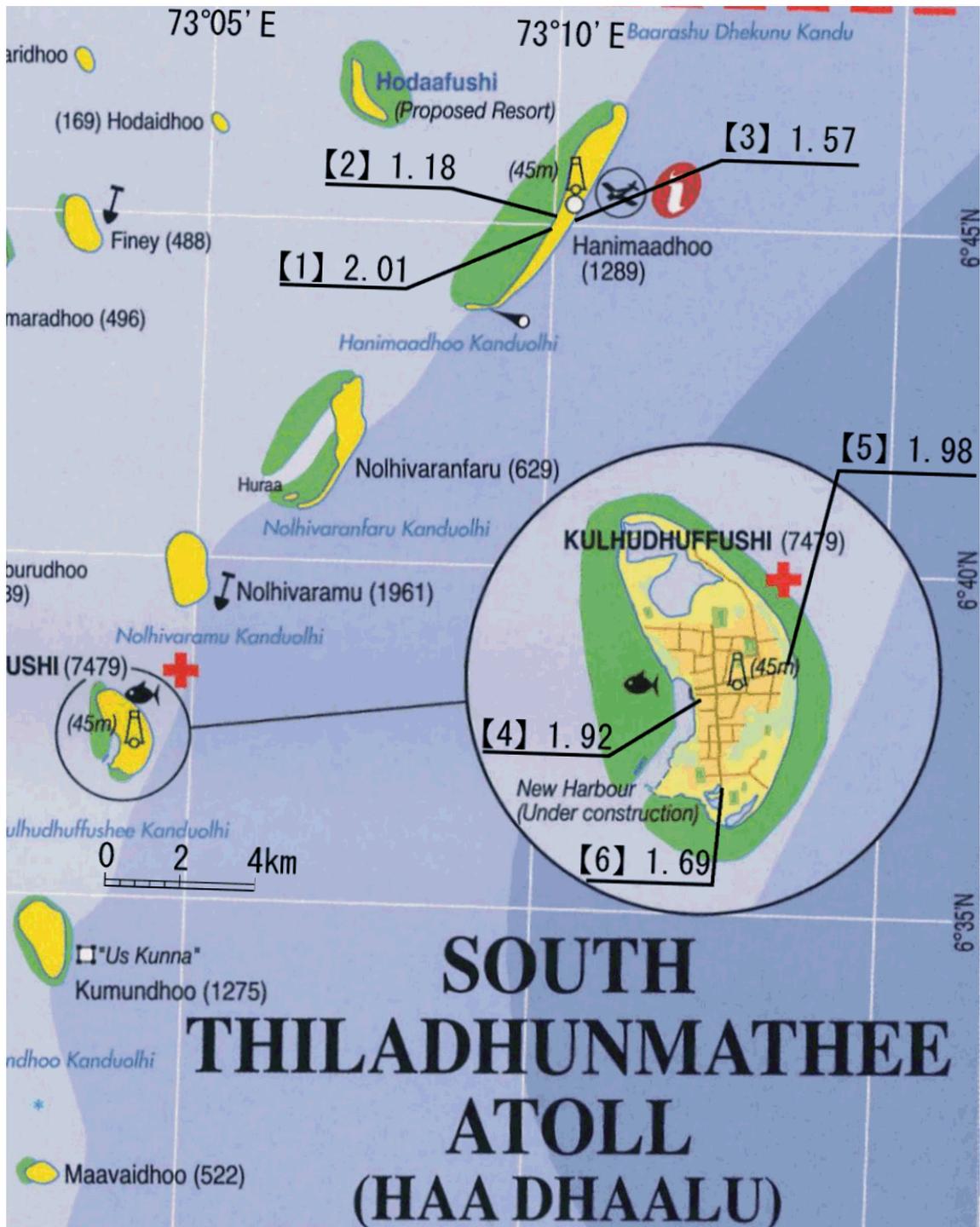


Figure 3.3.3 Surveyed Sites and the Tsunami Trace Height in Is. Hanimaadhoo and Is. Kulhudhuffushi (unit: m; Based map is from Atlas of the Maldives, 2004, ©Atoll Editions.)



Photo 3.3.1 Is. Kulhudhuffushi

We tried to summarize the tsunami attacks on Haa Dhaalu Atoll by viewpoints from circumstances of inundation and tsunami trace height, as written below.

(1) Results of Survey on Is. Hanimaadhoo

According to the residents, the tsunami intruded the island both from east and west sides of the coast at the same time, like the water level rises gradually. The airport buildings, which locate west side of the runway, were inundated; however, the runway was not.

In the residential area at northern Is. Hanimaadhoo, there are no such incidents like collapses of neither houses nor walls. According to the residents, inundation occurred at beaches of east and west, residential area did not receive any intrusion of seawater.

Since no clear marks of tsunami were found, hearings were conducted on the residents, and the heights of tsunami trace were measured. Figure 3.3.3 shows the location of measurement and the results. Photo 3.3.2 shows the sites.

(2) Results of Survey on Is. Kulhudhuffushi

According to hearings done on the residents of Is. Kulhudhuffushi, the tsunami came around both north and south of the island, and inundated the west area. It is found that the tsunami intruded the west coastal area from the north and the south.

The tsunami attacks on the Kulhudhuffushi could be summarized as below.

*West Coast

In the northern part of the west coast, collapsed houses and walls are observed (Photo 3.3.3). Several boats are thrown on the beach at the central part of the west coast.

*East Coast

Although Is. Kulhudhuffushis located the eastern end of the reef, the tsunami was blocked by berm, and little amount of tsunami body flew over it (Photo 3.3.3 site# **【5】**); however, it reached a house at 116.5 m inland by flew down on gently sloped ground toward west. The depth was 6 cm deep at the house.

*North Coast

No marks were found at the north coast. The coast is consisted of hard coral and has steep slope. Numerous fragments of coral, which thought to be transported by the tsunami, were found in inland.

*South Coast

It was found that the wall of Ministry of Public Works was collapsed. There were the clear marks at the wall of the yard(Photo 3.3.3 site# **【6】**).

In Is. Kulhudhuffushi, three clear tsunami marks were found and the heights were measured. One site, which a residence's witnessed, was also measured. Figure 3.3.3 shows points of measurement and tsunami trace height. The measured sites were photographed as shown in Photo 3.3.4.

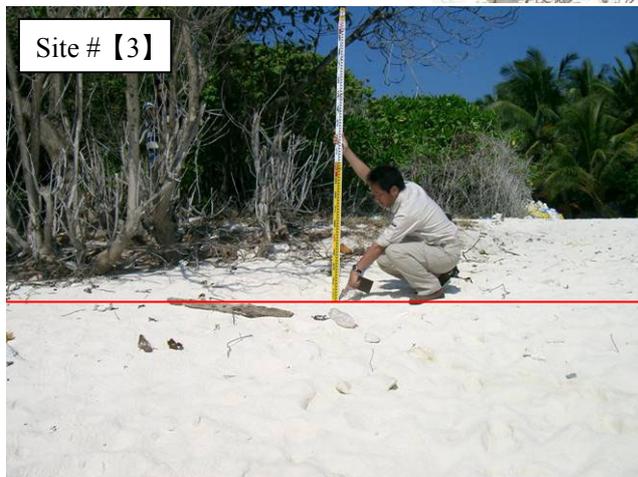


Photo 3.3.2 Site of Measurements in Is. Hanimaadhoo



Photo 3.3.3 Collapsed Wall at North West Part of the Is. Kulhudhuffushi

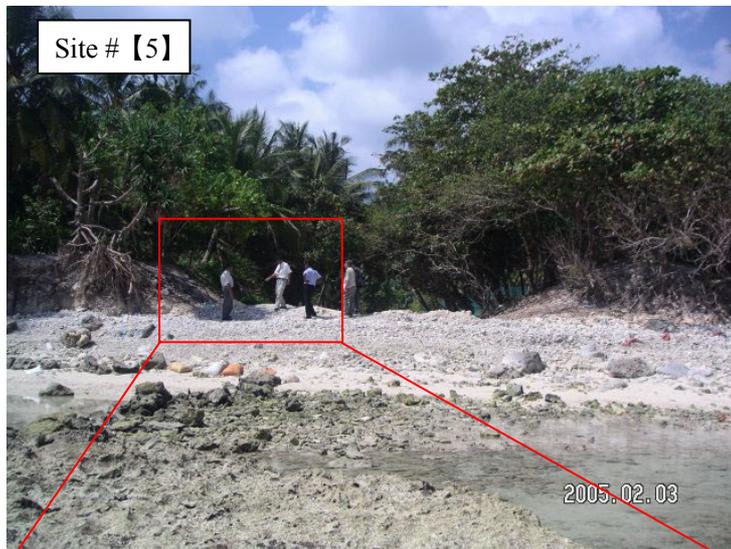
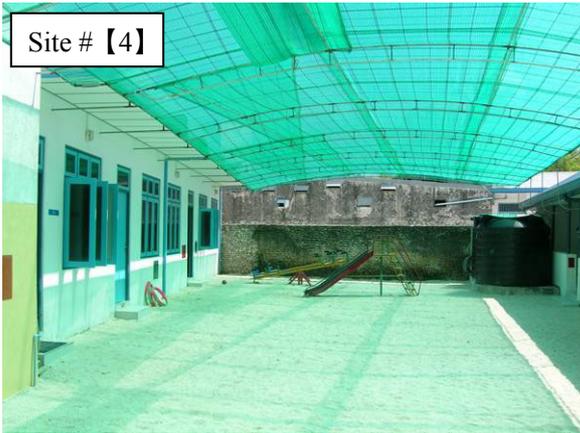


Photo 3.3.4(1) Measurement at Is. Kulhudhuffushi



Photo 3.3.4(2) Measurement at Is. Kulhudhuffushi

3.4 South Male' Atoll

South Male' Atoll faces Male' Island, which is the capital of the Republic of Maldives, along the Vaadhoo Channel to the north. The survey purposes are three points as follows;

1. The tsunami trace height distribution and arrival time in the region are surveyed,
2. The characteristic of main body of the tsunami energy which attacked not only this atoll along the channel but also Male' Island and Hulhule Island is made clear,
3. Information of natural environment damage is collected by the interview to scuba diving instructors of resorts.

The tsunami trace heights along the channel shown in Figure 3.4.1 were 0.65 to 1.38m. Laguna Beach Resort (photo 3.4.1) and Vadoo Island Resort (photo 3.4.2) were safe and no facilities in the islands were damaged. The maximum height 1.38m is almost same as the tidal gage record at Hulhule Island (International Airport). These results suggest that the tsunami energy progressed along the channel did not reduce well, and the right-angled energy against progressing was also almost same along there.

The height of water level at the inside of the atoll in Embudu Village (photo 3.4.3) was 1.33m, which was higher than that at the outside, 1.18m. This difference implies that the tsunami energy was held in the atoll. This island resort was also safe and was not damaged.

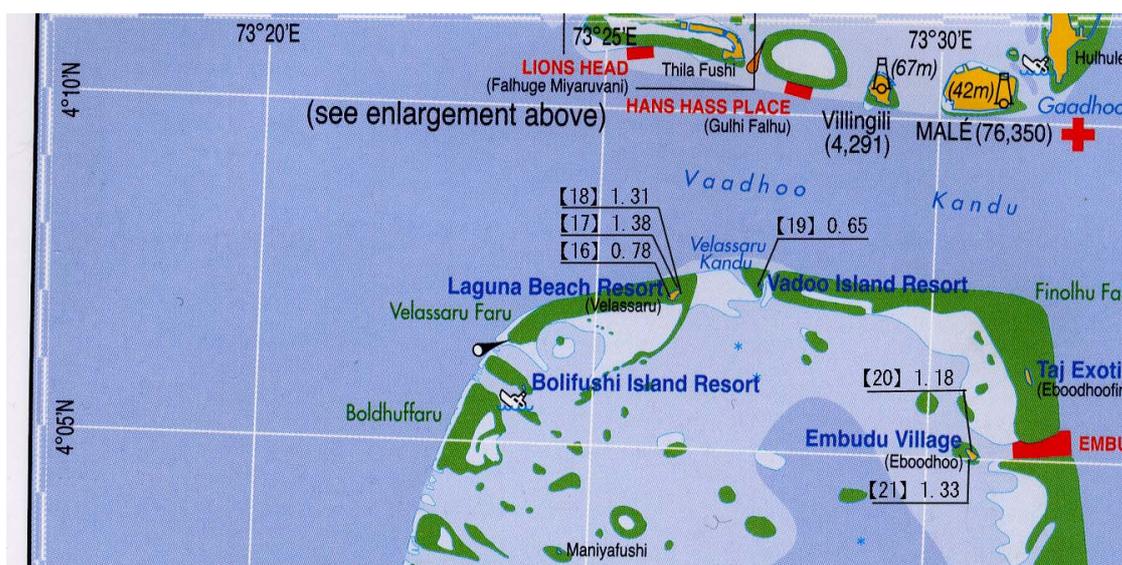


Figure 3.4.1 Tsunami trace heights in South Male' Atoll



Photo 3.4.1 Laguna Beach Resort



Photo 3.4.2 Vadoo Island Resort

The remarkable notes at each measured point are as follows;

No.16: A staff of Laguna Beach Resort witnessed the running-up tsunami at this west beach after checking inundation at north of the island. It means that he watched this beach a few minutes after the tsunami main body came.



Photo 3.4.3 Embudu Village

No.17: White sandy trace had remained under a cottage terrace of which level was below the cottage floor.

No.18: Same kind of white sandy trace had been on the side of flowerpot (photo 3.4.4). Wind waves on the tsunami from north overtopped sea walls.

No.19: Scuba diving instructors had measured this height at a step of pier (photo 3.4.5). They recognized the tsunami already had come to the Maldives before the water level raised because they found quite fast currents had occurred in a channel between Vaadhoo Channel and inside of this atoll.

No.20: One resort-beach staff in Embudu Village looked the tsunami and took the picture by his mobile phone near the pier which connects to cottages on the water (photo 3.4.6). The tsunami water level was a little lower than this island ground level. Some part of wind wave on the tsunami only ran and moistened the ground.

No.21: The owner and staffs witnessed that the water came from the inside of the atoll to the level just below the restaurant's floor.



Photo 3.4.4

Trace at Laguna Beach Resort



Photo 3.4.5

Trace at Vadoo Island Resort



Photo 3.4.6

Trace at Embudu Village

Observed by Vadoo Island Resort E→W 3/5
1/2H

08:30	CC	
09:10	N→S	SLOW
09:11	N→S	STORONG X3 水位 40cm 上げ
09:13		EXIT
09:23		水位 1m 上がる
09:28	S→N	STORONG X3
09:30		水位 1m 下がる
09:45		水位 1m 下がる
09:50	N→S	STORONG X3 水位 40cm 上げ
09:55	N→S	STORONG 水位 20cm 下がる
09:58	N→S	SLOW
10:00	N→S	3 水位 40cm 下がる
10:05	N→S	STORONG X3
10:08		水位 20cm 下がる
10:15	S→N	STORONG X3 水位 40cm 上げ
10:30	S→N	STORONG 水位 40cm 上げ
10:35	N→S	STORONG X3 水位 40cm 上げ
10:40	N→S	STORONG X3 水位 40cm 上げ
10:43	N→S	STORONG X3 水位 20cm 上げ
10:46	N→S	STORONG X3 水位 20cm 上げ
10:49	N→S	STORONG X3 水位 20cm 上げ
10:50	N→S	STORONG X3 水位 40cm 上げ
10:55	N→S	STORONG 水位 20cm 上げ
11:00	S→N	3
11:02	S→N	STORONG X3 水位 30cm 上げ
11:03	S→N	STORONG X3 水位 MAX
11:06	S→N	STORONG X3 水位 40cm 上げ
11:15	S→N	SLOW

Figure 3.4.2 Tsunami Record provided by Vadoo Island Resort

At 9:11 AM on 26th December, Japanese scuba diving instructors of Vadoo Islands Resort received the initial impact of tsunami in a small channel along this island. They noted down the currents and water level fluctuation to a sheet, which is shown in Figure 3.4.2 and Figure 3.4.3.

The '9:11' is remarkable time because of the earliest record of the tsunami in the Maldives. In order to check the safety before visitors dive, one instructor was diving as routine work at the small channel along the island which connects from Vaadhoo

Channel to inside of the atoll. The current directed to inside of the atoll was too fast for the professional of diving, did not let him swim or stay by holding a rock either. He escaped to inside of the atoll because he knows that currents in the inside are slow as compared with those in the small channel.

As celerity of a tsunami is fast in the deep sea, the water

level in Vaadhoo Channel rose earlier than the record of the tidal gage at Hulhule Airport. Since the energy concentrated to the progressing direction, the gradient of water level between the channel and the atoll became steep. This was the driving force of the initial fast current.

In the inside of South Male's Atoll, the large strong circulation was witnessed during a few hours, of which direction changed many times clockwise and counter-clockwise. The phenomena also express a part of tsunami energy was held and fluctuated in the atoll. On the other hand, another scuba diving instructor did not feel tsunami or strong current at a northern area of Vaadhoo Channel.

The following natural environment damages were watched by the resort staffs and the scuba diving instructors.

- A heavy coral rock of which weight was about a few hundred kilograms moved.
- Much silt and sand moved to deep zone where water depth is 15m or more than.
- Turbidity in the channel and atoll rose by silt of corals during two weeks after the tsunami attacking. Many staffs of resorts described that sea water around islands

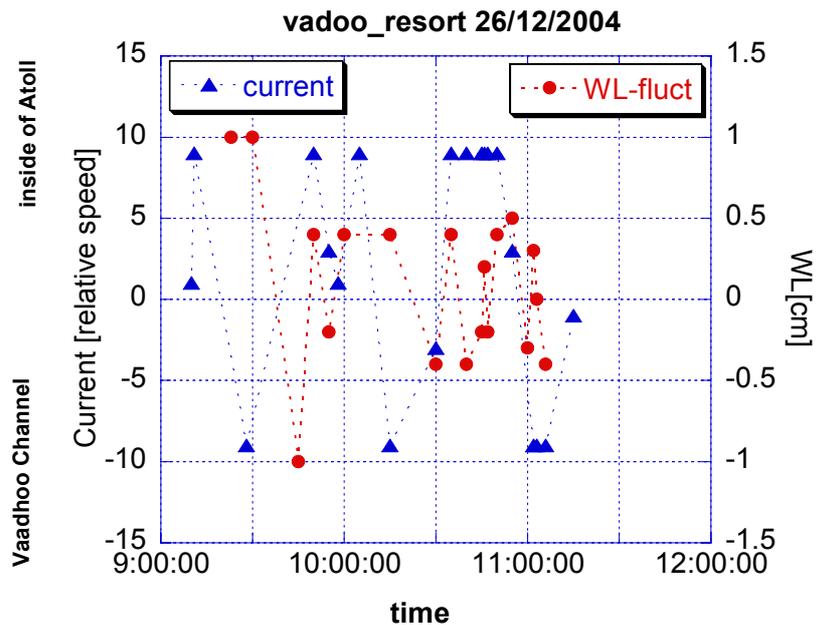


Figure 3.4.3 Tsunami records at Vadoo Islands Resort

became milk color.

- Small branching corals were damaged at some area along Vaadhoo Channel.
- Some branching and poritidae corals rolled off from shallow area to deep area.
- Some middle size of branching corals was also damaged. On the other hand, no large branching coral over 1m in diameter was damaged.
- Many corals from top reefs to 15m depth area have been covered by the sand. Particularly the covering has been taking place inside of the Atoll.
- Many kind and number of fishes disappeared in and around the atoll at once just after tsunami. All of these fishes, however, came back soon.

3.5 Vaavu Atoll

Keyodhoo is located in the center of east side of the Vaavu atoll, Nobody died in the island. According to hearing on the residents, the tsunami came two times. The leading wave went through from east to west (see Photo 3.5.1), and the second intruded the both sides of the coast at the same. Moreover, the ground water in the well changed salty after the tsunami attack. The tsunami trace heights measured in this island are indicated in Figure 3.5.1. Photo 3.5.2 describes trace of tsunami in house. Everywhere were inundated about 1m above the ground in the island.



Photo 3.5.1 Direction of tsunami in Keyodhoo

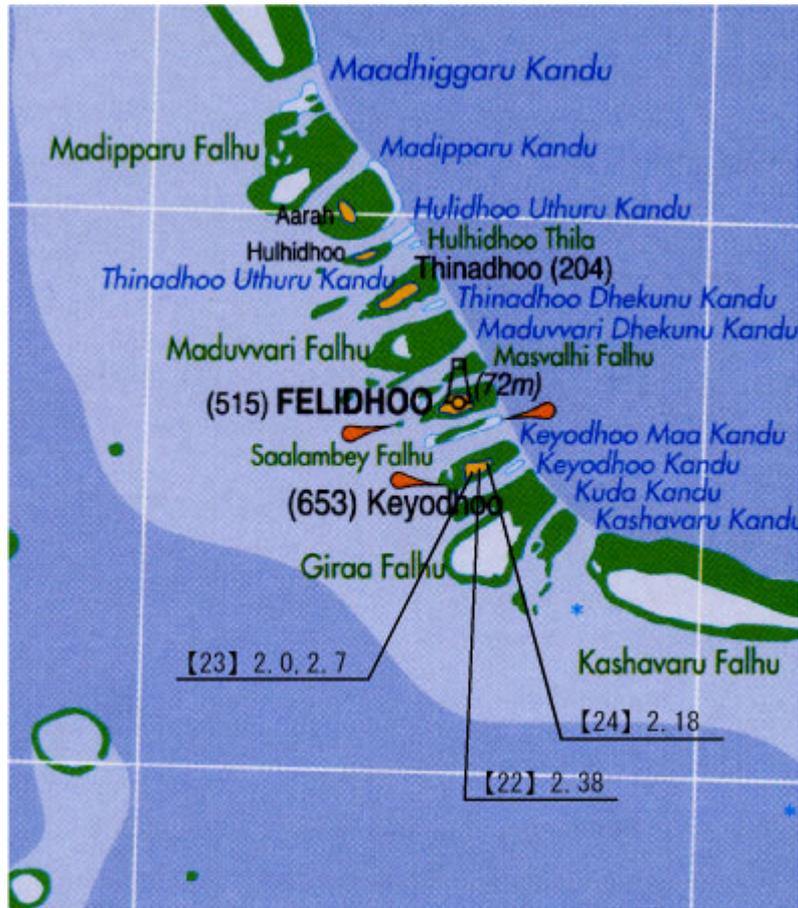


Figure 3.5.1 Measured tsunami trace heights (inundation and run up) in Keyodhoo (Vaavu Atoll)



Photo 3.5.2 Trace of the tsunami on wall in a house (1.08m of water level from the ground)

3.6 Meemu Atoll

Muli is located in the south east of the Meemu atoll, 5 people died and 1 person is still missing. According to eyewitnesses, the tsunami went through from east to west, and the leading wave was the highest. That can be explained from the measured inundation height as shown in Figure 3.6.1. The tsunami trace heights were recorded approximately 3m in the east side and 2m in the west. Photo 3.6.2 shows coastal erosion by the tsunami in west side. It is understand that step of several dozen centimeter is formed.



Photo 3.6.1 Direction of tsunami in Muli



Figure 3.6.1 Measured tsunami trace heights (inundation and run up) in Muli (Meemu Atoll)



Photo 3.6.2 Coastal erosion by tsunami in west coast. Red arrow indicates the direction of tsunami.

3.7 Dhaalu Atoll

3.7.1 Ribudhoo

Ribudhoo is in the north-east inside the Dhaalu atoll, there are no deaths in the island. The wave came two times and intruded the east and west sides at the same in Photo 3.7.1. After that, all over in the island is inundated and the water level repeated up and down during the tsunami coming. Photo 3.7.2 indicates the tsunami was raised to the line of the breast. In Figure 3.7.1, it is found that the tsunami trace heights cross over 3m even if the island is located inside atoll.

3.7.2 Gemendhoo

Gemendhoo, located in the center of east side of the Dhaalu atoll, is one of the island which suffered the most serious damage in the Maldives. 5 people were killed and 3 people are missing in the island. The tsunami went through from east to west (see Photo 3.7.3), about 3m of tsunami trace heights were investigated at each point as shown Figure 3.7.2. Since a lot of houses and physical plants were destroyed in the island (see Photo 3.7.4), most residents evacuated to a shelter in other island. Photo 3.7.5 shows damage of erosion by the tsunami. Resident in the island indicates at the ground surface level lower 10cm approximately.



Photo 3.7.1 Direction of tsunami in Ribudhoo

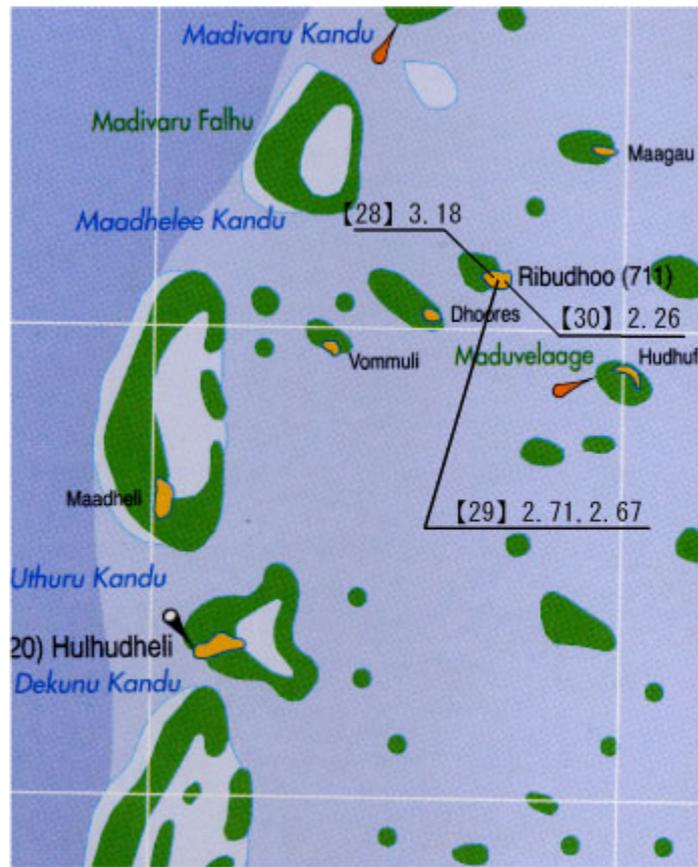


Figure 3.7.1 Measured tsunami trace heights (inundation and run up) in Ribudhoo (Dhaalu Atoll)



Photo 3.7.2 Tsunami trace on wall at central of the island



Photo 3.7.3 Direction of tsunami in Gemendhoo



Figure 3.7.2 Measured tsunami trace heights (inundation and run up) in Gemendhoo (Dhaalu Atoll)



Photo 3.7.4 Electric light bent by tsunamis



Photo 3.7.5 Sand erosion by tsunamis. Spacing red arrow indicates thickness of sands eroded by tsunamis.

3.8 Laamu Atoll

Laamu Atoll is one of the heavy damaged atolls in the Maldives by the tsunami (photo 3.8.1, 3.8.2). Twenty-two people died, three people are missing and more than 285 buildings were damaged. This is the reason why this atoll was chosen to survey the tsunami inundation heights.



Photo 3.8.2 Fonadhoo Is.

Photo 3.8.1 Kaddhoo and Fonadhoo Is. in Laamu Atoll

Tsunami trace heights were surveyed in four islands named Gan, Maandhoo, Kaddhoo, and Fonadhoo. Each island is close to a neighboring island and those are connecting by a road of sand banks. Inundation heights in the islands were 2.08 to 3.22m in the ocean side (east of the islands) and 1.28 to 1.93m in the atoll side as shown in Figure 3.8.1. Only the houses at the ocean side were damaged (photo 3.8.3), particularly in Fonadhoo where four

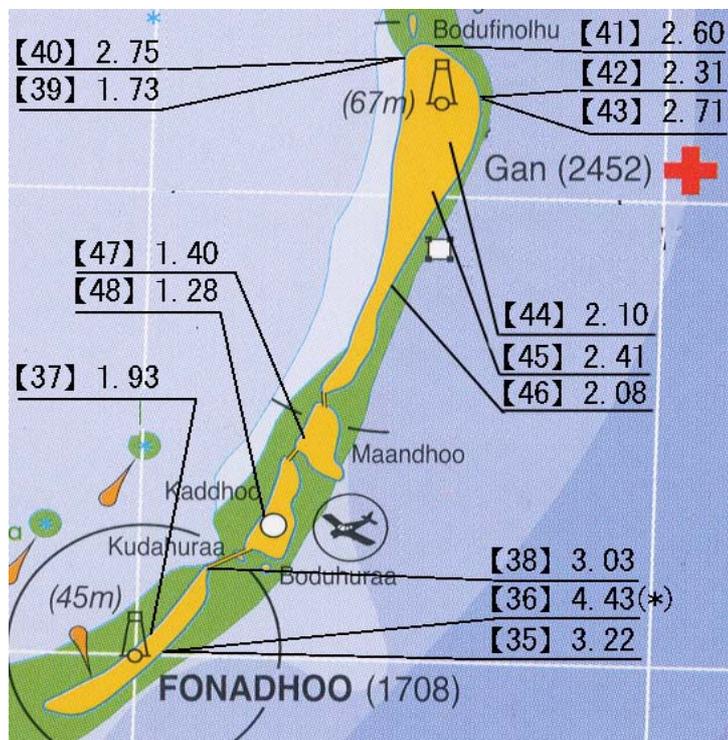


Figure 3.8.1 Tsunami trace heights in Laamu Atoll



Photo 3.8.3 Map of completely damaged houses (red marks)

inhabitants died. These results show tsunami attacked from ocean side and progressed to the atoll side, which agreed with evidences of inhabitants and the report of Japanese journalist of Tokyo Newspaper, who visited here on 30th December.

The remarkable notes of each measured point are as follows;

No.35: The traces of sand lines have remained on the inside and outside walls of a house (Photo 3.8.4). Fonadhoo Village is close to the ocean and has lower density of trees along the coastal line than that of the other villages. The inundation height which was '3.22m' is the highest record in the trustworthy records in this atoll.

No.36: The height was maximum level of running-up water to a house wall based on the inhabitant evidence. This house was across a road from No.35.

No.37: Mud trace had remained on an inside wall of a garage near a coast of the atoll side (Photo 3.8.5).

No.38: The tracer was beach sandal having hanged on a branch of a tree (Photo 3.8.6). Some hurt branches were higher level than that of sandal. But these were not confirmed as a trace by the tsunami or others. Here is the entrance of Fonadhoo Island from the road and naked sandy area, which means that there was no resistant against the tsunami. One traffic lane, the road to Kaddhoo from Fonadhoo, collapsed by the tsunami (Photo 3.8.7).

No.39: This area is almost northernmost in Gan Island and faces to atoll side. Each of

three house's walls had fallen down in each direction as showing the tsunami attacked from several directions.

No.40: A plastic bag has been hanging on a branch of tree. This point is on the beach near the No.39.

No.41: ditto

No.42: The tracer here is a plastic bag on a branch too. There are no houses for a long time and there are one road and forests around here.

No.43: This point is close to No.42

No.44: Sandy lines have remained on a house's wall. The height record here was about 50cm lower than that of inhabitant's evidence. She said the water level attained her waist.

The weak wall and house along the roads to each direction in the village were damaged as shown that the water body of the tsunami passed on the roads.

No.45: This record is based on the witness, who is a young worker at an electric power house. He said that this level kept for five minutes. The water level shown by sandy trace was 70cm lower than initial level, and had stayed for two hours.

No.46: Thin sandy line had been on the wall of a house. Residence also said this is a trace. She said that 'these children ran and escaped to west coast of the atoll side when the inundation came'. She was in another island when the disaster occurred.

No.47: Sandy traces had remained on the wall of one facility in a fishery base in Maandhoo. This base was developed in the atoll side and large forest is preserved at ocean side. As pointing to the straight road which led to the east coast, one staff said that the inundation level had inclined, that the level at the east had been high and that in west coast had been low. Second tsunami came from inside of the atoll.

No.48: Airport staffs showed the inundation height at the front of Airport terminal. There are large forests between east coast and this airport.

By comparing of damaged houses in these islands, we believe that a little high ground level and sandy berm and a little large forest reduced the tsunami energy much. Photo 3.8.13 shows typical situations along the Gan coast. Particularly, ground level is important to reduce that. Figure 3.8.2 shows the comparison of ground level elevation on the four measured line. The berms in Gan are higher than that in Fonadhoo which was damaged heavily. It is very important to preserve natural resistances like sand berms and forests against a tsunami.



Photo 3.8.4 Trace at the No.35 in Fonadhoo



Photo 3.8.5 Trace at the No.37 in Fonadhoo



Photo 3.8.6 Trace at the No.38 in Fonadhoo



Photo 3.8.7 Collapsed connecting road



Photo 3.8.8 Trace at the No.43 in Gan



Photo 3.8.9 Trace at the No.44 in Gan



Photo 3.8.10 Trace at the No.45 in Gan



Photo 3.8.11 Trace at the No.46 in Gan



Photo 3.8.12 Trace at the No.47 in Maandhoo



Photo 3.8.13 Typical shape at Gan coast

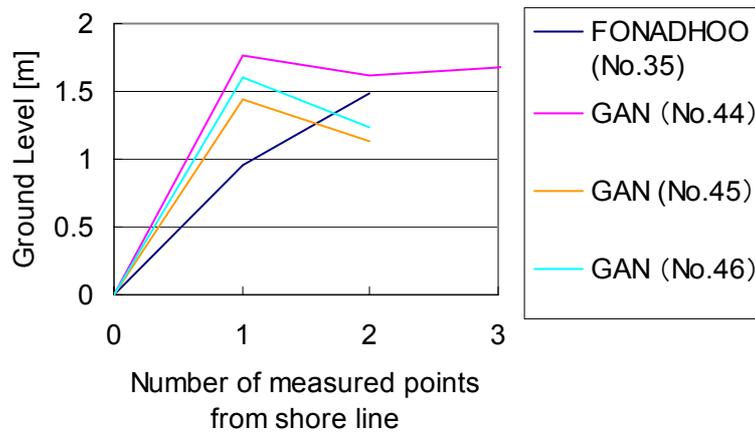


Figure 3.8.2 Ground level distributions

3.9 Seenu Atoll

3.9.1 Introduction

The Seenu Atoll is the southernmost part of the Maldives and lies between latitude $0^{\circ} 35' 40''$ S to $0^{\circ} 42' 30''$ S and longitude $73^{\circ} 04' 30''$ E to $73^{\circ} 14' 43''$ E as shown in Figure.3.9.1. It has 4 main gaps of coral reefs. Two of them are located at north part of the Atoll, named as Maa Kandu and Kuda Kandu. Others are located at southeast part of the Atoll, named as Viligili Kandu and Gan Kandu.

The survey team (Dr.Tomita, Mr.Honda and Mr.Hanzawa) visited the Seenu Atoll on 3rd February 2005 and carried out site survey on the west part of the Atoll. The team covered islands of Gan, Feydhoo, Maradhoo, Maradhoo and Hithadhoo.

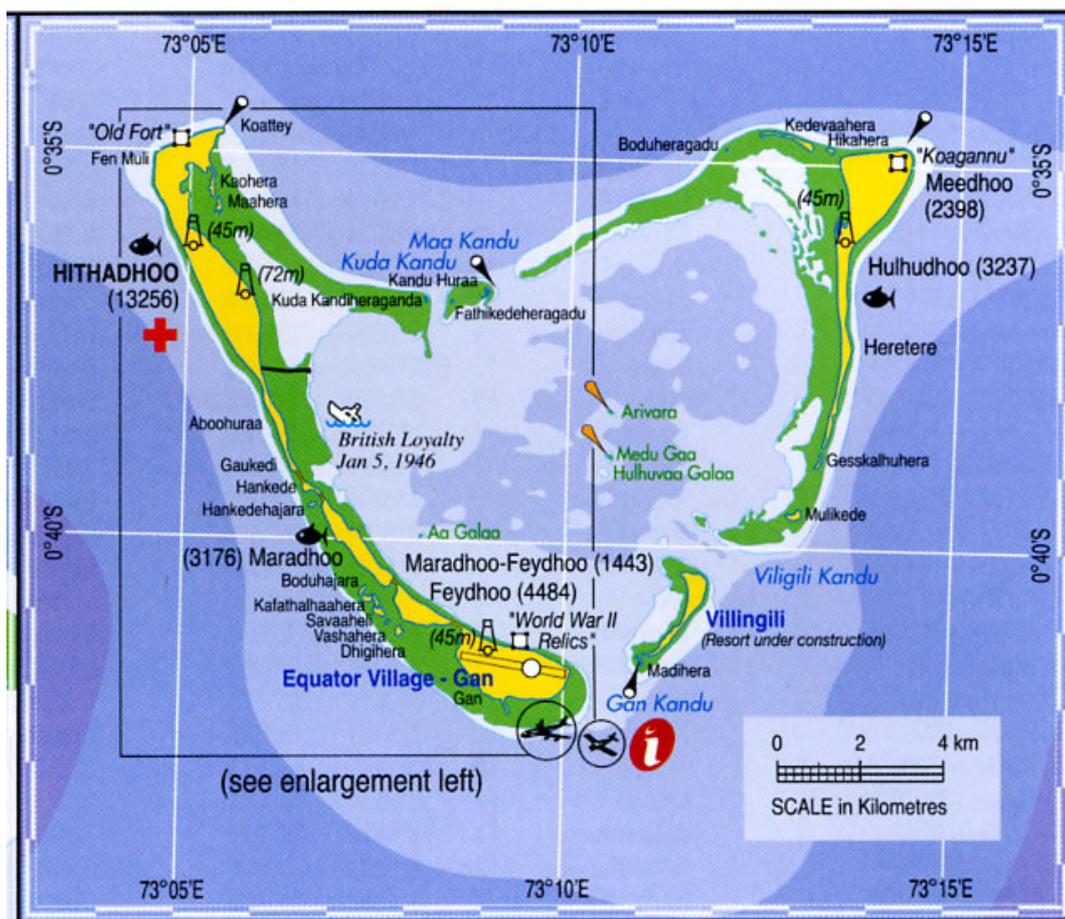


Figure 3.9.1 Map of the Seenu Atoll

3.9.2 Tsunami in Seenu Atoll

It is reported that the tsunami came basically from the east (inside the atoll) to the west (open sea) in Seenu Atoll. It seems that the tsunami invaded to the atoll through both north Kandus (Maa and Kuda) and southeast Kandus (Viligili and Gan) based on the interview in the survey area.

Sea level change during the tsunami attack was successfully recorded by Mr. Sugita, Wakachiku Construction Co., Ltd., at the project site in Hithadhoo. Figure 3.9.2 shows the site map and the table of the tide record and Photo 3.9.1 shows the location of the tide recording. The water levels were measured from the crown of the quay and they were converted to the values above the construction datum level (CDL). The MSL (mean sea level) at the site and the level of the crown of the quay are +2.40m and +0.75m above CDL respectively. Figure 3.9.3 shows the sketch of those relations. Figure 3.9.4 shows the time series of tide record based on the table in Figure. 3.9.2.

Date : 26/12/2004

Time	Measurement	Tide
09:25	1,45	0,95
09:26	1,20	1,20
09:27	1,00	1,40
09:28	0,90	1,50
09:30	0,85	1,55
09:32	1,10	1,30
09:35	1,15	1,25
09:39	1,50	0,90
09:41	2,15	0,25
09:43	2,20	0,20
09:44	2,05	0,35
09:47	2,55	-0,15
09:47	1,85	0,55
09:51	2,35	0,05
09:56	3,25	-0,85
10:00	2,20	0,20
10:03	1,85	0,55
10:04	1,85	0,55
10:15	1,70	0,70
10:17	1,25	1,15
10:19	1,60	0,80
10:22	1,70	0,70
10:23	2,15	0,25
10:26	1,60	0,80
10:28	1,65	0,75
10:32	1,45	0,95
10:34	2,05	0,35
10:35	1,95	0,45
10:37	1,95	0,45
10:40	1,95	0,45
10:42	1,65	0,75
10:43	2,05	0,35
10:44	1,90	0,50
10:45	1,85	0,55
10:48	1,95	0,45
10:49	1,85	0,55
10:51	1,85	0,55
10:53	1,75	0,65
10:55	1,40	1,00
10:58	1,30	1,10
11:00	1,70	0,70
11:05	1,45	0,95
11:08	1,45	0,95
11:11	1,70	0,70
11:12	1,85	0,55
11:14	1,70	0,70
11:18	1,60	0,80
11:21	1,40	1,00
11:25	1,75	0,65
11:30	1,65	0,75
11:35	1,80	0,60
11:40	1,70	0,70
11:45	1,55	0,85
11:50	1,50	0,90
11:55	1,40	1,00
12:00	1,20	1,20
12:40	1,55	0,85
12:45	1,45	0,95
12:50	1,55	0,85
12:55	1,35	1,05
13:00	1,35	1,05
13:05	1,60	0,80
13:10	1,45	0,95

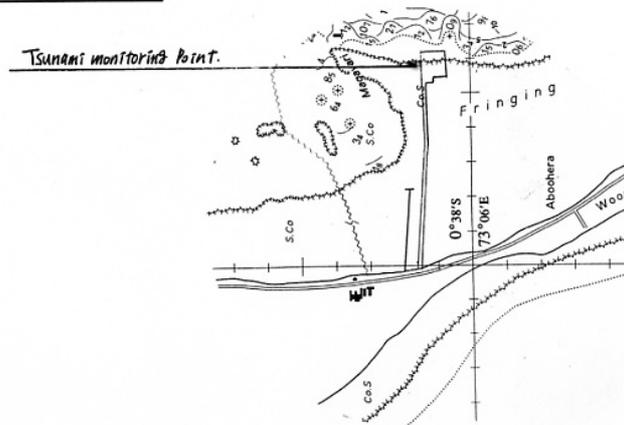
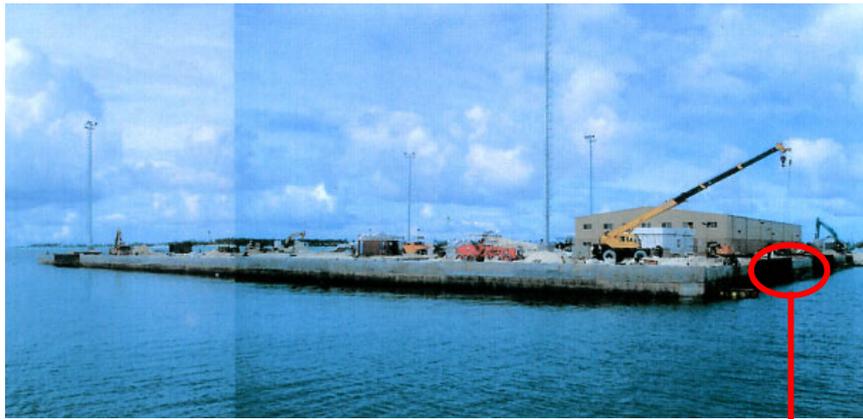


Figure 3.9.2 Site Map of the Tide Recording and Table of Measured Record by Mr.Sugita



Tide Recording Position

Photo 3.9.1 Location of Tide Recording

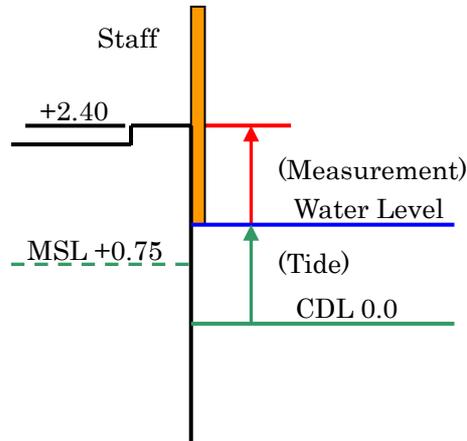


Figure 3.9.3 Sketch of Tide Measurement

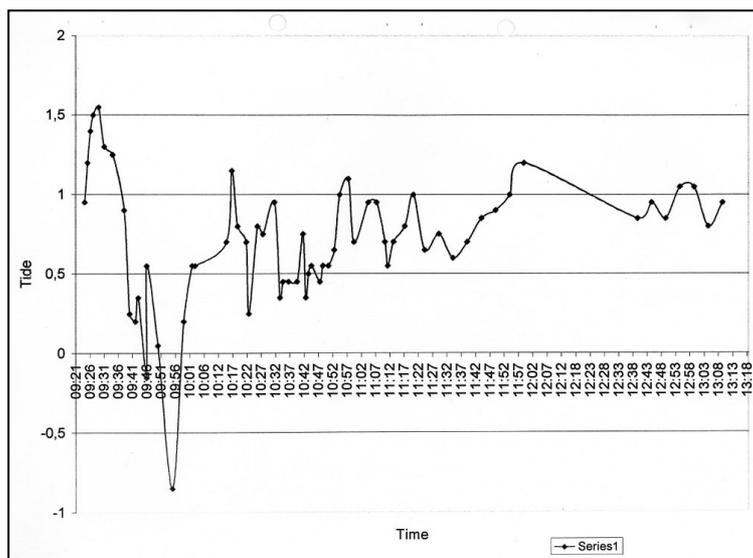


Figure 3.9.4 Time series of Tide Record above CDL by Mr.Sugita

Figure 3.9.5 shows the water level variation recorded at Wakachiku site in Hithadhoo mentioned above converted to values above MSL together with predicted and actual water levels at Gan Island (0°41' S, 73°09' E) based on web pages of the University of Hawaii Sea Level Center. The maximum water level at Gan reached 0.8m and the minimum -0.5m. As for tide change at Hithadhoo, the maximum reached 0.8m same as Gan, however, the minimum -1.6m far below Gan. The net water level changes affected by the tsunami at up-rush phase at Gan and Hithadhoo are estimated at 1.0m and those at backwash phase are estimated at 0.4m and 1.5m respectively. Large difference observed at backwash phase is considered to be caused by topography difference. According to the interview at Feydhoo, Maradhoofeydhoo, Maradhoo and Hithadhoo, water level change at backwash phase was larger than that at up-rush phase. These observations can be explained and supported by the tide variation recorded at Hithadhoo.

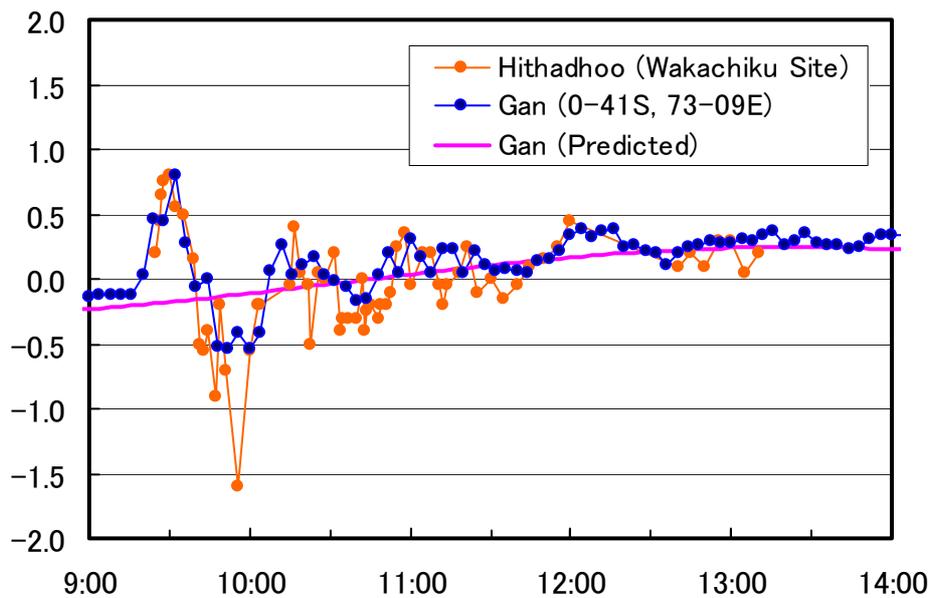


Figure 3.9.5 Comparison of Water Level Changes above MSL at Hithadhoo and Gan

3.9.3 Tsunami Trace Height and Damage

The survey team measured the tsunami run-up and inundation height along the east side of survey area of Gan, Feydhoo, Maradhoofeydhoo, Maradhoo and Hithadhoo, because the tsunami attacked from east side in this area. Run-up and inundation heights were specified at totally 11 points based on interview and traces on walls, etc. The results of the survey at those points are shown in Figure. 3.9.6 as No.49 to 59. In

the figure the marks “<x” and “x<” mean “smaller than x” and “larger than x” respectively. Those results are discussed again by location with damage observation in following sections.

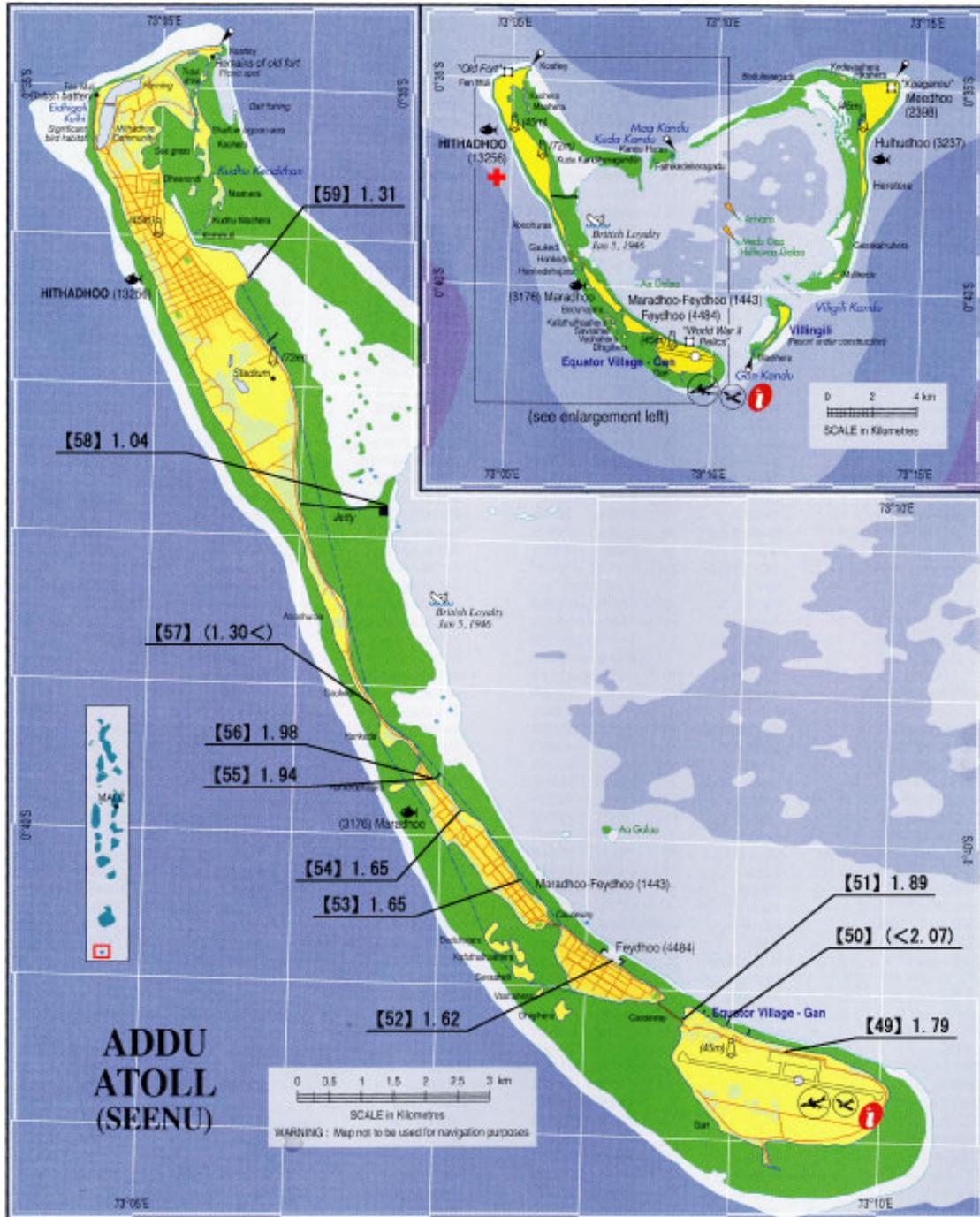


Figure 3.9.6 Tsunami Trace Height

1) Gan

The first location of survey in Gan Island was around the construction site of new international airport terminal building. Two-way road is running between the building and seashore. The tsunami at this place considered to have reached about center of the road. This run-up height is estimated at 1.79m as shown in Figure 3.9.6 as Point No.49. The seashore in front of the terminal building facing inside the atoll was damaged by the tsunami as shown in Photo 3.9.2.

The second survey location was the jetty. The crown level of this jetty is 2.07m and the tsunami height did not reach this level as shown in Figure 3.9.6 as Point No.50 with the figure of <2.07m.

The third survey location was around the junction of the causeway and the northeast seawall. According to the interview to security officers, the water level rise was observed first at 9:00 am on 26th December. The tsunami came from inside the atoll and three main tsunami waves were observed with interval of 5 to 10 minutes. The first one was the biggest. They also said that the tsunami attack was not like wave but like sea level rise and down. The seawall was damaged by the tsunami and the crown part (super structure) have moved to seaward 1.0m from the initial position as shown in Photo 3.9.4. The reason of this damage is considered that back fill of the sea wall was sucked out because of extreme low water level at the backwash phase of the tsunami. The inundation height of this place was about 0.3m above crown level as shown in Photo 3.9.5 by arm of Mr.Sugita. This height was estimated at 1.89m as shown in Figure 3.9.6 as Point No.51 that is just the corner of starting point of the causeway where the crown level was measured.



Photo 3.9.2 Seashore in front of Terminal Bldg.



Photo 3.9.3 Jetty in Gan



Photo 3.9.4 Damage of Seawall



Photo 3.9.5 Run-up Height at Seawall

2) Feydhoo

The survey was carried out around the fishing harbour in Feydhoo. The witnesses said that water level in this area moved up and down for 30 to 40 times within the period of 45 minutes from 9:00am. The water level rose up suddenly and kept high level for about 20 to 30 seconds, then suddenly went down. The highest water level reached just above crown of quay wall shown in Photo 3.9.6. The run-up height was estimated at 1.62m as shown in Figure 3.9.6 as Point No.52. At the time of the minimum water level, the sea bottom of 5m below HWL 1.0m above LWL could be seen, resulting turning over of fishing boat which was under repair in ship yard in Hithadhoo. The detached breakwater made of coral stones was partially damaged by the tsunami as shown in Photo 3.9.7.



Photo 3.9.6 Seawall of Fishing Harbour



Photo 3.9.7 Detached Breakwater

3) Maradhoofeydhoo

The fishing harbour in Maradhoofeydhoo was surveyed. The witnesses said that the tsunami reached the crown level of the detached breakwater shown in Photo 3.9.8 and run-up height was estimated at 1.65m at the seawall as shown in Figure 3.9.6 as Point No.53. They said that speed of water level rise was almost the same as backwash.



Photo 3.9.8 Detached Breakwater in Fishing Harbour

4) Maradhoo

Two locations were surveyed in Maradhoo. The first one was fishing harbour. The witnesses said that three waves of the tsunami came to this area and the first one was observed at 9:15am followed by the second and third ones with interval of 5 to 10 minutes. They said that the second one was biggest and the tsunami height was about 1.5m. The inundation height was estimated at 1.65m as shown in Figure 3.9.6 as Point No.54. The sea bottom could be seen at the time of minimum sea level and 5 seconds after the minimum sea level was reached then next tsunami came. The seawall in this harbour was cracked and moved to seaward by the tsunami as shown in Photo 3.9.9. The seawall is considered to move to seaward still now.

The second location of the survey was around the shipyard. The inundation heights were surveyed at two points. The results were 1.94m at Point No.55 and 1.98m at Point No.56 as shown in Figure 3.9.6. Point No.56 was ship repair yard and there was the tsunami trace on the wall of house near ship repair yard as shown in Photo 3.9.10. Photo 3.9.11 shows the perspective of the wall from seashore.



Photo 3.9.9 Seawall Damage in Fishing Harbour

House with Tsunami Trace in Photo



Photo 3.9.10 Trace of Tsunami



Photo 3.9.11 Perspective from Seashore

5) Hithadhoo

Three locations were surveyed in Hithadhoo. The first one was around the road located at southernmost area in Hithadhoo, and the inundation height was estimated larger than 1.3m as shown in Figure 3.9.6 as Point No.57. Sand beach became like rocky by sand erosion caused by the tsunami.

The second location was the regional port construction (Wakachiku) site as shown before in Photo 3.9.1 and tide recording was carried out in this site as described before in Chapter 3.9.2. The maximum tsunami height was 1.04m as shown in Figure 3.9.6 as Point No.58

The third location was around Hithadhoo Harbour shown in Photo 3.9.12 and

3.9.13. The seawall has two crown levels. The tsunami ran over the lower part and reached 15cm below the high crown level. The inundation height was estimated at 1.31m as shown in Figure 3.9.6 as Point No.59



Photos 3.9.12 (Left) and 3.9.13 (Right) Seawall in Hithadhoo Harbour

3.9.4 Summary

The tsunami in the Seenu Atoll came from east and the maximum water level reached 0.8m above MSL both in Gan and Hithadhoo and the minimum reached -0.5m in Gan and -1.6m in Hithadhoo. The run-up or inundation heights along the islands of Gan, Feydhoo, Maradhoofeydhoo, Maradhoo and Hithadhoo were estimated at 1.5 to 2.0m. The seawalls in Gan and Maradhoo were damaged by the tsunami resulting in seaward movement of crown part. The detached breakwater made mainly of coral stones were partially damaged in Feydhoo and Maradhoofeydhoo.

In addition to the survey results, it is reported by the witnesses that Maa Kandu became shallower because of the tsunami resulting in difficulties in ship maneuvering.

The survey team members wish to express their sincere gratitude to Mr. Sugita, Wakachiku Construction Co., Ltd. for his full support including his offer of tide data recorded at Wakachiku project site in Hithadhoo and to Mr. Mohamad Aslam, Maavahi for his useful information on the Seenu Atoll, his guide to specific place of survey and translation from local language to English. The team members wish to thank all persons concerned in survey area for their useful information on the tsunami.