NUMERICAL STUDY ON THE SEAWALL'S EFFECT
AGAINST SUMATRA TSUNAMI RUN-UP AT MALE' ISLAND

By

Fuminori KATO

National Institute for Land and Infrastructure Management (1 Asahi Tsukuba-shi, Ibaraki 305-0804, Japan)

Masaya FUKUHAMA

National Institute for Land and Infrastructure Management (1 Asahi Tsukuba-shi, Ibaraki 305-0804, Japan)

Yasuro OHTANI

Alpha Hydraulic Engineering Consultants Co., Ltd. Tokyo Branch (4-15-35 Mita, Minato-ku Tokyo 103-0073, Japan)

Yugo IMAZU

Alpha Hydraulic Engineering Consultants Co., Ltd (9-14-516-336 Hassamu, Nishi-ku Sapporo-shi, Hokkaido 063-0829, Japan)

Takuya SAKAWA

Alpha Hydraulic Engineering Consultants Co., Ltd (9-14-516-336 Hassamu, Nishi-ku Sapporo-shi, Hokkaido 063-0829, Japan)

and

Kentaro HAYASHI

Alpha Hydraulic Engineering Consultants Co., Ltd (9-14-516-336 Hassamu, Nishi-ku Sapporo-shi, Hokkaido 063-0829, Japan)

SYNOPSIS

Male' Island, the capital of Maldives, was hit by the Smatra Tsunami on December 26 2004, but the damage was less severe in comparison with other islands in the Maldives and neighboring countries. One of the major reasons was attributed to the solid seawalls surrounding the island. In this study, the effects of the seawalls are investigated by means of a numerical simulation, in which the finest grid size is 3.33m covering whole Male' Island. The results indicate that Male' Island without seawalls would have been hit by run-up flows with higher energy several times, especially on the east coast facing to the tsunami source. Thus, it is certain that the existing seawalls reduced the damage of Male' Island as far as this incident is concerned. In fact, the maximum tsunami height in Maldives, however, was relatively small, approx. 2m, so that the existing seawalls worked well against the tsunami. For larger tsunamis, the effects of the shore protection facilities would become smaller. Therefore, it is essential to set up a comprehensive prevention system which includes

non-constructive methods such as tsunami forecasts, warnings, and an evacuation guiding system in preparation for larger scale tsunamis.

INTRODUCTION

A huge earthquake occurred off the west coast of northern Sumatra, Indonesia, on December 26, 2004. The magnitude of this earthquake was estimated to be 9.0. The tsunami generated by this earthquake spread across the entire Indian Ocean and caused serious damages to the coastal areas of surrounding countries. The casualties of this event were reported from not only Indonesia and neighboring countries but also from Sri Lanka, India, Maldives and even from some African nations thousands kilometers away from the epicenter. The UN office (http://www.tsunamispecialenvoy.org/country/humantoll.asp) reported that total 229,866 people were killed or went missing by this event. Reasons why the damages became so extensive would include a lack of forecasts and a warning system for tsunami, little recognition about what a tsunami is, and inadequate preparations for tsunami.

In the coastal areas around Indian Ocean, there are little shore protection structures except for harbor zones. Male' Island, the capital of the Republic of Maldives, is, however, surrounded by solid seawalls constructed by Japan's Official Development Assistance. Therefore, it is believed that these facilities may have played a role in reducing damages caused by the tsunami. In fact, nobody was killed on Male' Island, where almost a third of the whole dense population (approximately 80,000 people) lives densely, while 58 people were killed in the Maldives.

This study investigates the behaviors (inundation and flow condition) of the tsunami which hit on Male' Island quantitatively by using a elaborated numerical simulation and discusses the effects of the solid seawall structures for reducing the damages by comparing the simulation results of with- and without- existing seawalls.

AN OVERVIEW OF MALE' ISLAND AND ITS DAMAGE FROM SMATRA TSUNAMI

The Republic of Maldives, as shown in Fig.1, consists of 26 atolls of various sizes ranging within the area of about 820km (north and south) and 130km (east and west). Although Male' is a small island as less than 2 square kilometers, it is the capital of the Maldives and is located on the southern end of North Male Atoll, it has highly dense population of about 80,000 equal to almost one-third of the whole of the Maldives. With a lot of office buildings and residences close together in Male Island, it is literally the center of the politics and the economy in the Maldives.

Because the land elevation is no more than 1.5m above the mean sea level (M.S.L.) as shown in Fig.2, Male Island has experienced disasters by storm surges many times, and is also in danger of being submerged by the rise of mean sea level due to global warming. The island has been enlarged by reclamation by the edge of the reef. As a result, the slope of the seabed has become sharp, particularly in the southeast coast facing the edge of the atoll, the quite steep slope falls to the depth of 2000m even in areas about 20km off the coast.

Since Male' island suffered from serious damages by storm surges with big waves both in 1987 and 1988, seawalls and the offshore breakwaters have been constructed (Fig.3). The elevation of the seawalls was designed by considering the design wave heights at each coast as +2.16 to +2.56m above mean sea level (M.S.L.) for the east coast, M.S.L. +1.46 to +3.36m for the south coast, and M.S.L. +1.96 to +2.36m for the west coast. In the northern and southern harbor zones, the elevation of quays is M.S.L. +1.16m. Furthermore, the south coast is protected by the offshore breakwaters.

According to the eyewitnesses of Sumatra tsunami (inquired on March 5, 2005), when the first wave hit the east

coast, the water level rose up to about 1m above the seawalls, whose crown height is M.S.L.+2.56m, and remained at that elevation for 5-10 minutes. Then a second wave whose height was 0.5m followed after the water level once dropped to as low as the seabed around the jetties appeared. Some people at the north coast also reported that the tsunami height had been approximately 1m above the ground level of the quay.

As described above, the magnitude of inundation on the Male' Island was not so large that nobody was killed. Furthermore, the fact that the most of buildings were made of concrete would play a role in reducing the number of deaths. On the other hand, on the other islands of the Maldives, this tsunami caused 82 deaths and 26 people went missing in all, because few coastal protections had been built and because most of houses were made of simple cemented corallites.
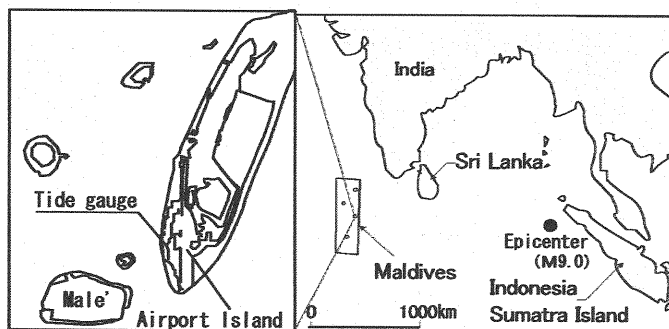
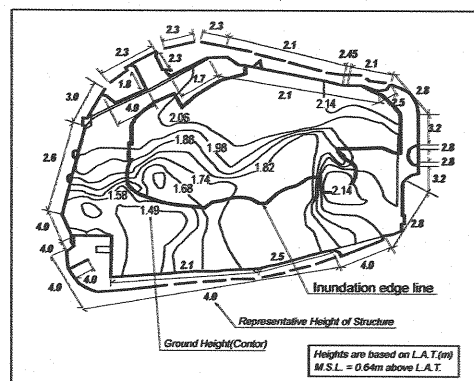Fig. 1   Location of Maldives

Fig. 2   Ground height of Male' Island with measured inundation edge line (Fujima et al. (1))
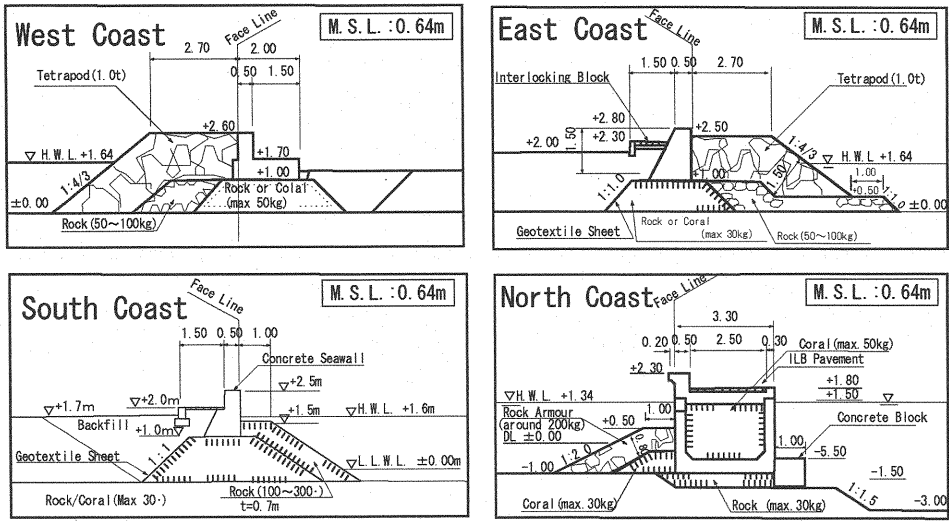
Fig. 3   Coastal protection facilities surrounding Male' Island

NUMERICAL MODELING OF TSUNAMI

A numerical model employed to simulate tsunami propagation and run-up is based on the non-linear shallow water equations equipped with the terms of bottom friction, turbulent and the Coriolis forces.

$$\frac{\partial \eta}{\partial t} + \frac{\partial P}{\partial x} + \frac{\partial Q}{\partial y} = 0 \tag{1}$$

$$\frac{\partial P}{\partial t} + \frac{\partial}{\partial x}\left(\frac{P^2}{D}\right) + \frac{\partial}{\partial y}\left(\frac{PQ}{D}\right) + gD\frac{\partial \eta}{\partial x} + \frac{gPn^2\sqrt{P^2+Q^2}}{D^{7/3}} - \frac{\partial}{\partial x}\left(ED\frac{\partial}{\partial x}\left(\frac{P}{D}\right)\right) - \frac{\partial}{\partial y}\left(ED\frac{\partial}{\partial y}\left(\frac{P}{D}\right)\right) - \Omega Q = 0 \tag{2}$$

$$\frac{\partial Q}{\partial t} + \frac{\partial}{\partial x}\left(\frac{PQ}{D}\right) + \frac{\partial}{\partial y}\left(\frac{Q^2}{D}\right) + gD\frac{\partial \eta}{\partial y} + \frac{gQn^2\sqrt{P^2+Q^2}}{D^{7/3}} - \frac{\partial}{\partial x}\left(ED\frac{\partial}{\partial x}\left(\frac{Q}{D}\right)\right) - \frac{\partial}{\partial y}\left(ED\frac{\partial}{\partial y}\left(\frac{Q}{D}\right)\right) + \Omega P = 0 \tag{3}$$

where η = the water surface elevation; P and Q = the line discharge in the x and y direction; D = the total water depth; E = the eddy viscosity; n = the Manning's roughness coefficient; Ω = the Coriolis parameter; and g = the gravity acceleration.

The distribution of sea bottom deformations was computed from fault parameters based on the liner elastic theory (Mansinha and Smylie (2)) and given as the initial sea surface profile. Table 1 shows the fault parameters (Koshimura et al. (3)), which explains the tide record at Maldives' best in the preliminary simulations. (The definition of fault parameters is illustrated in Fig.4.) With these parameter sets, the dimension of the fault was estimated to be 150km(Width) and 900km(Length) empirically, and then it was split into two segments (South 500km and North 400km) to match the distribution of after shocks.

Table 1   Fault parameters

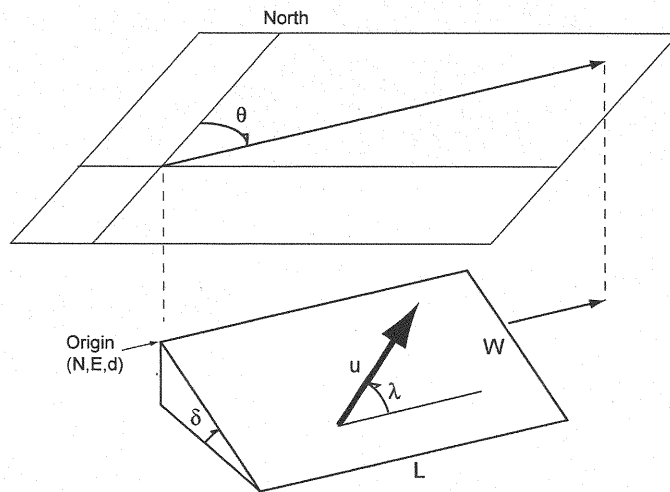|	1st. Segment (Southern part)	2nd. Segment (Northern part)
Strike θ(degree)	329	358
Dip δ(degree)	15	15
Slip λ(degree)	90	90
Length L(km)	500	400
Width W(km)	150	150
Dislocation u(m)	11	11
Fault Depth d(km)	10	10
Longitude E(degree)	2.5 N	6.5 N
Latitude N(degree)	94.8 E	92.0 E

Fig. 4   Definition of the fault parameters

This tsunami simulation was performed in two stages. The first stage was the tsunami propagation in the large area, covering the North Indian Ocean from Indonesia to Maldives with a single resolution of 2430m. The second stage simulated the run-up flow conditions on Male' Island with 7-area-nested model. The finest resolution of the model is 3.33m for whole Male' Island. The time series of the water levels and the flow fluxes derived from the first stage simulation were given for the 4 boundary conditions at this stage. (See Table 2 and Fig.5)

Table 2   Construction of models

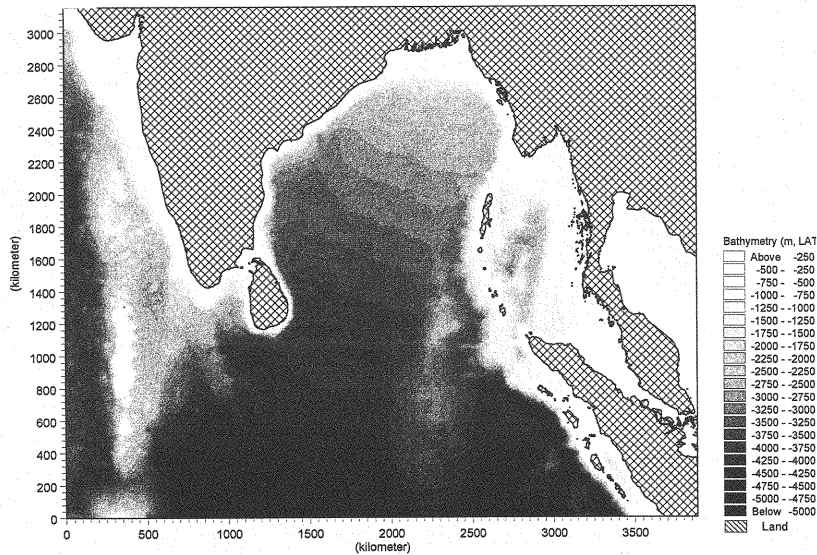|	Area	Resolution	Number of grids		Remarks
First stage	0	2430 m	1600	x 1300	Including tsunami source
Second stage (nested model)	1	2430 m	241	x 451	Forced boundary condition from area 0
	2	810 m	34	x 34	
	3	270 m	40	x 37	
	4	90 m	55	x 46	
	5	30 m	100	x 76	
	6	10 m	235	x 163	
	7	3.33 m	649	x 430	Whole Male' Island

Fig. 5   Simulation domains and their topographies

The time intervals were set as 1.00 sec in the first stage and 0.25 sec in the second stage to satisfy the CFL condition. Also, the astronomical tide level was kept constant both in time and space during the simulation as + 0.58m from the Lowest Astronomical Tide (L.A.T.) (equal to –0.06m from the M.S.L. at the coast of Male' Island), which is the same tide level when the tsunami arrived in the Maldives.

In conventional tsunami run-up simulations, structures such as buildings and houses have been evaluated as equivalent to the bed roughness, and have been chosen according to the density of structures (e.g. Aburaya et al. (4)). Probably, one of the major reasons for this was the limitation of computer performance which made it necessary to set the grid size for the same or larger than scale of buildings (the order of 10^1 m). In recent years, however, tsunami simulations with 10^0 m order resolution have been almost in practical use, which would have also been contributed by improvement of the land survey technology. In this study, since the finest resolution was 3.33m on Male' Island, we could have expressed each houses separately. However, since we couldn't obtain sufficient information to identify all the houses on Male' Island, we confined our investigation to 3 types of land use of road, empty lots and high dense residence blocks (see Fig.6). The high dense residence blocks are modeled as uniformly 10m higher than the basement of surroundings (10 m was supposed to be the typical building height and it was expected that the tsunami would not pass over or penetrate.) The roads and empty lots are distinguished by two different Manning's roughness coefficients of 0.020 and 0.025, respectively. Although this simulation was conducted by applying the simplicities mentioned above, it showed better accordance with what happened in reality than the conventional methods did. The reason for this is that the most of the tsunami run-up would inundate through the road on Male' Island, not through the openings between houses. In other words, evaluating houses into several blocks didn't yield any worse results for the simulation. Incidentally the roughness for seabed is set as 0.025.
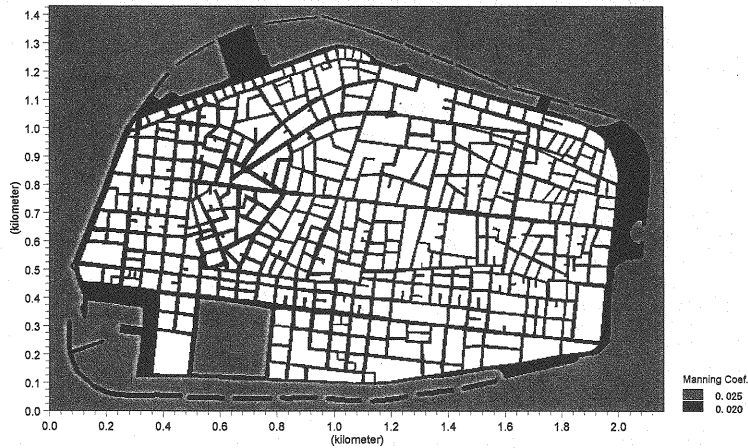
Fig. 6   Allocation of Manning's roughness coefficient on Male' Island
(White zones show the high dense residence blocks that were supposed to be impervious and not going to be destroyed by tsunami).

The topographic data was created on the basis of charts, and for the levels of the land and the seawalls' crown heights on Male' Island we referred to the results of the field survey (Fujima et al. (1))(See Fig.2 and Fig.6). As shown in Fig.2, the land elevation becomes relatively higher towards northeast. The white sections in Fig.6 indicate the high dense residence blocks. The breakwaters in the north and south coasts were also introduced into the model.

TSUNAMI PROPAGATION

Fig.7 shows the snaps of simulated tsunami propagation in the Indian Ocean (the first stage of the simulation). As the tectonics of this region suggests the thrust fault as the focal mechanism, initial tsunami profile showed subsidence on the east side of the fault and uplifts on the west side. The tsunami propagates mainly eastward (starts with fall) and westward (starts with rising), and then just half an hour after the earthquake, the first tsunami crest hit the northern coast of Sumatra Island soon after the ebb. The tsunami reaches Sri Lanka in 2 hours and Male' Island in about 3.5 hours.

This tsunami was recorded on the tide gauge at Male' International Airport (see Fig.1). Fig.8 shows the comparison of the water level fluctuations at Male' between the results of the simulation and the measurements. The effects of astronomical tide were removed from the raw measurement records. Both in the simulation and the measurement, the first wave, which began with rising, arrived at almost the same time, and followed by the second and the third crests at intervals of about 40 minutes. The simulation results show good agreements with the measurements, especially around the arrival time and the maximum tsunami height (about 2 m for the first wave). The short period oscillations are a little more prominent in the simulation in comparison with the measurements. One reason for this could be the numerical model used in this study did not include the decay of the short period fluctuations caused by the effects of the wave dispersion.
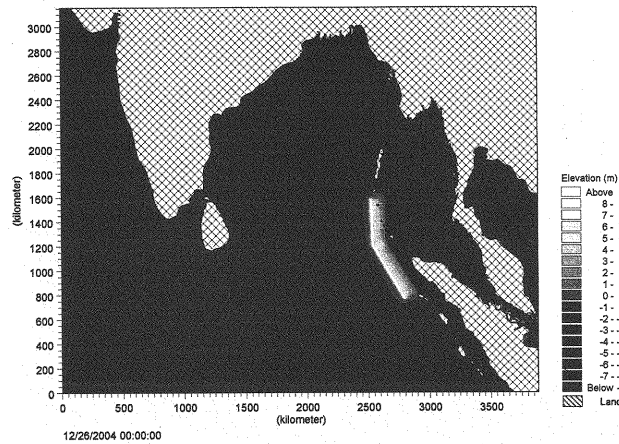
Fig. 7   Initial surface elevations in the first stage simulation

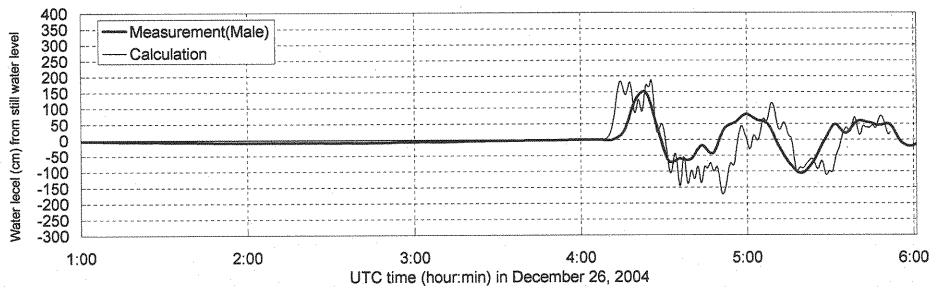(Brighter areas are relatively higher.)

Fig. 8   Comparison of the water levels at Airport Island (see FIg.1) between the simulation and the measurement

(The contribution of astronomical tide was removed from the raw measurement records.)

RUN-UP ON MALE' ISLAND

Fig.9 shows the run-up progress as the water level distributions on Male' Island that came along with the first wave. Fig.10 shows the time series of the water level monitored at the points found as open circles in Fig.9. Because it had been confirmed that the first wave was the biggest in Male' Island both from the measurements and the first stage simulation, we focused our attention on the first wave. As can be seen in Fig.10, the arrival of the first wave is about 90 seconds earlier in the south and the east coasts than in the north and the west coasts. This suggests that the first wave came to Male' Island from southeast and then propagated behind the island. For the next 20 minutes, the water level in the south and the east coasts oscillated with the averaged amplitude of 1m in 2-4 minute periods, especially in the east coast, which is facing to the wave direction, the amplitude tends to be larger and reaches about 3m at around 4:20(Coordinated Universal Time;

UTC). Similar type of oscillations has been seen in the north and the west coasts. The amplitudes were, however, smaller than those in the other coasts. The reason for this is that those coasts or sides are just sheltered by the island. Our explanation for the cause of the oscillations was mainly the interference by reflections from surrounding atolls and islands.

In a comparison between Fig.9 and Fig.10, we can see that the inundation begins from the south coast around 4:15, when the water levels at the south and the east coasts rise at to around 2.0 m. Just before 4:25, the water level on the east coast reaches a maximum level of 2.5m, at beginning of starting the inundation. By 4:30, when the water level around Male' had fallen, the inundation had also begun in the north coast, and the flooded area continued growing even at 4:40 when the water level kept falling down.

Finally, Fig.11 shows the distribution of simulated maximum inundation height comparing with the measured inundation boarder (Fujima et al. (1)). The white sections in the figure represent the high dense residence blocks, assuming that the tsunami would not pass over or penetrate into them in this model. According to the results of the surveys, approximately 60% of the Island was inundated, especially the southern half and western part of the island were inundated widely, and the non-inundation area almost overlapped the shape of primitive (before the reclamation) Male' Island. The simulated inundation boarder shows good agreements with the measurements in spite of a lack of some detailed geometry data. However, a previous numerical study conducted by Ohtani et al. (5) made a simulatinon almost similar to us, but a little larger in the inundation area than ours. The differences could mainly have been caused by the difference of modeling method, that is, the resistances of houses were simply included as equivalent bed roughness in the previous study which we did not do.
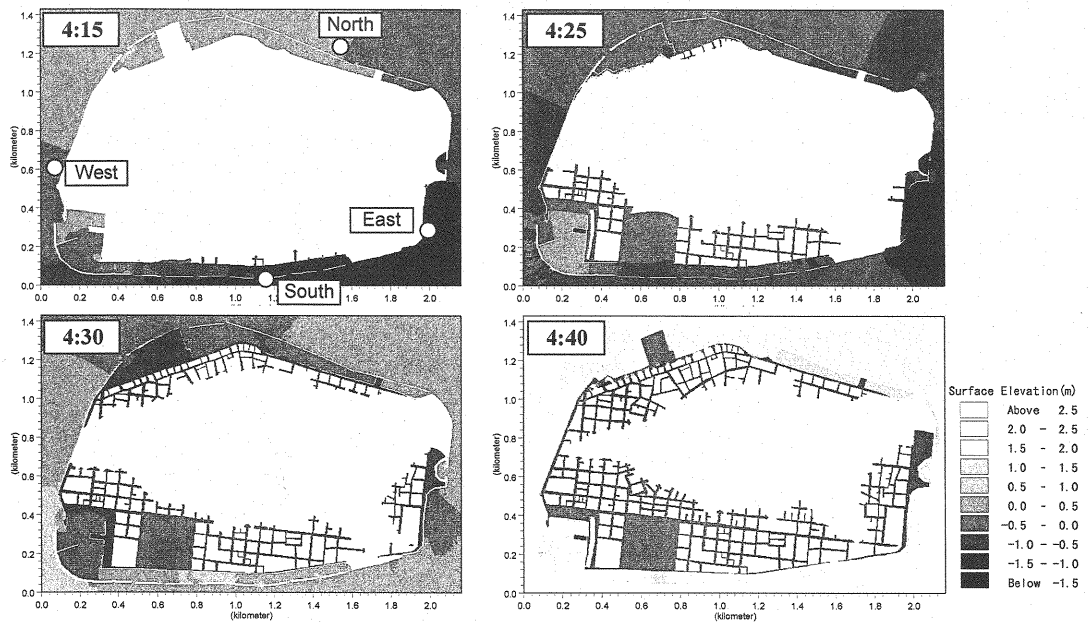

Fig. 9   Run-up process on Male' Island that came along with the first wave
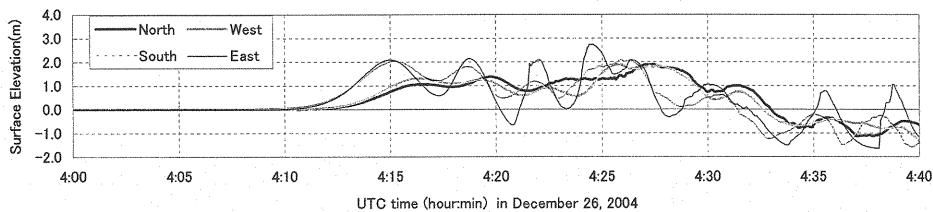
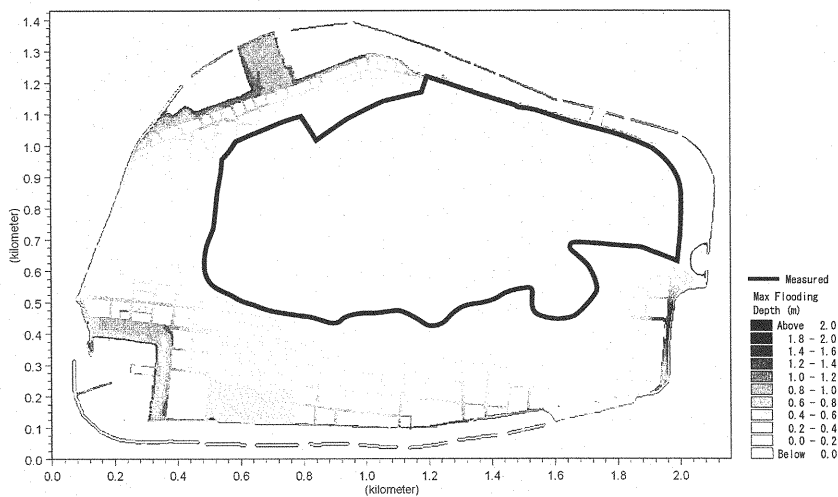Fig. 10   Time series of water level around Male' Island (points are found in Fig.9)

Fig. 11   Simulated maximum flooding depth on Male' Island and measured inundation border.
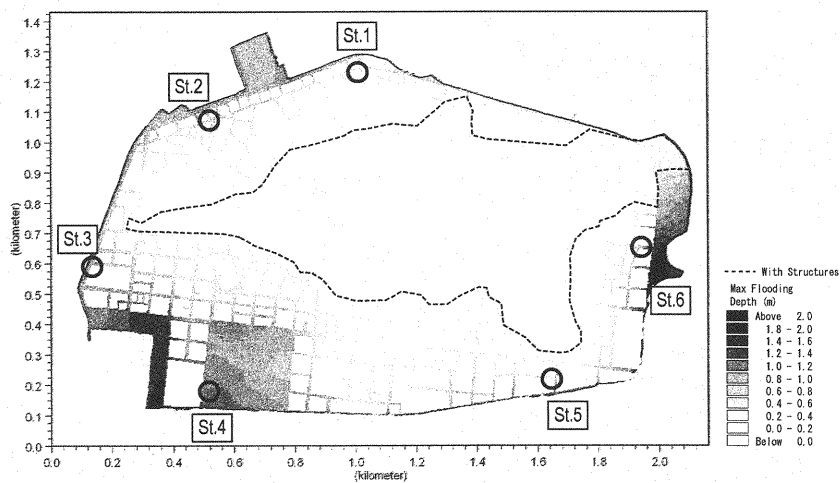

Fig. 12   Simulated maximum flooding depth on Male' Island without seawalls and breakwaters.

DISCUSSION ON THE EFFECTS OF SEAWALLS

Fig.12 shows the results of the scenario simulation assuming that all the structures (all the seawalls and breakwaters) are absent. The dashed line represents the inundation border given by the simulation with the present condition (Fig.11). Both the inundated area and the inundation depth increase for the case without structures. More than 1m increase of inundation depth is estimated around the area behind the seawalls at southeast part in Male' island. In addition, some increases in the inundation depths are simulated at openings and quay walls in the southwest part. In the north part, however, no significant increases of inundation levels are estimated, since present seawalls are low.

Fig.13 shows the comparisons of the inundation depths at each location (indicated in Fig.12) with and without the structures. At St.1 and 2, located in north part, no significant difference of the inundation depths is estimated. This is due to the low elevation of the seawalls. For the other locations, however, the effects of the seawalls show significant differences. For instance, without the structures, some areas began to be inundated earlier and the maximum inundation levels are almost twice as that with the structures. For St.4, St.5 and St.6, which are located at south and east coast, the inundation level seems to be varying as the water level is changing shown in Fig.10.

Fig.14 shows comparisons of the flow velocity at each location for the cases with and without the structures. At St.1, 2, and 3, the effect of the seawalls is small. The flow velocity at the St. 3 is initially small compared with those of other locations. This is because St.3 is located on the other side of the place where the tsunami first reaches. For St.4 through 6, the maximum flow velocity was about 0.5 m/s with the structures and 1.5 m/s without them, especially at St. 5 and 6, where the tsunami first reached in the island, the flow velocities are much larger for the case without the structures.

The tsunami approaching from the east of the island would start inundating at both the east and south shore. It is thought that the seawalls prevented the inundation from southeast, but made tsunami inundate form southwest part, which is at a relatively lower elevation. Findings also revealed that the seawalls play a role in reducing the inundation on land and the flow velocity.
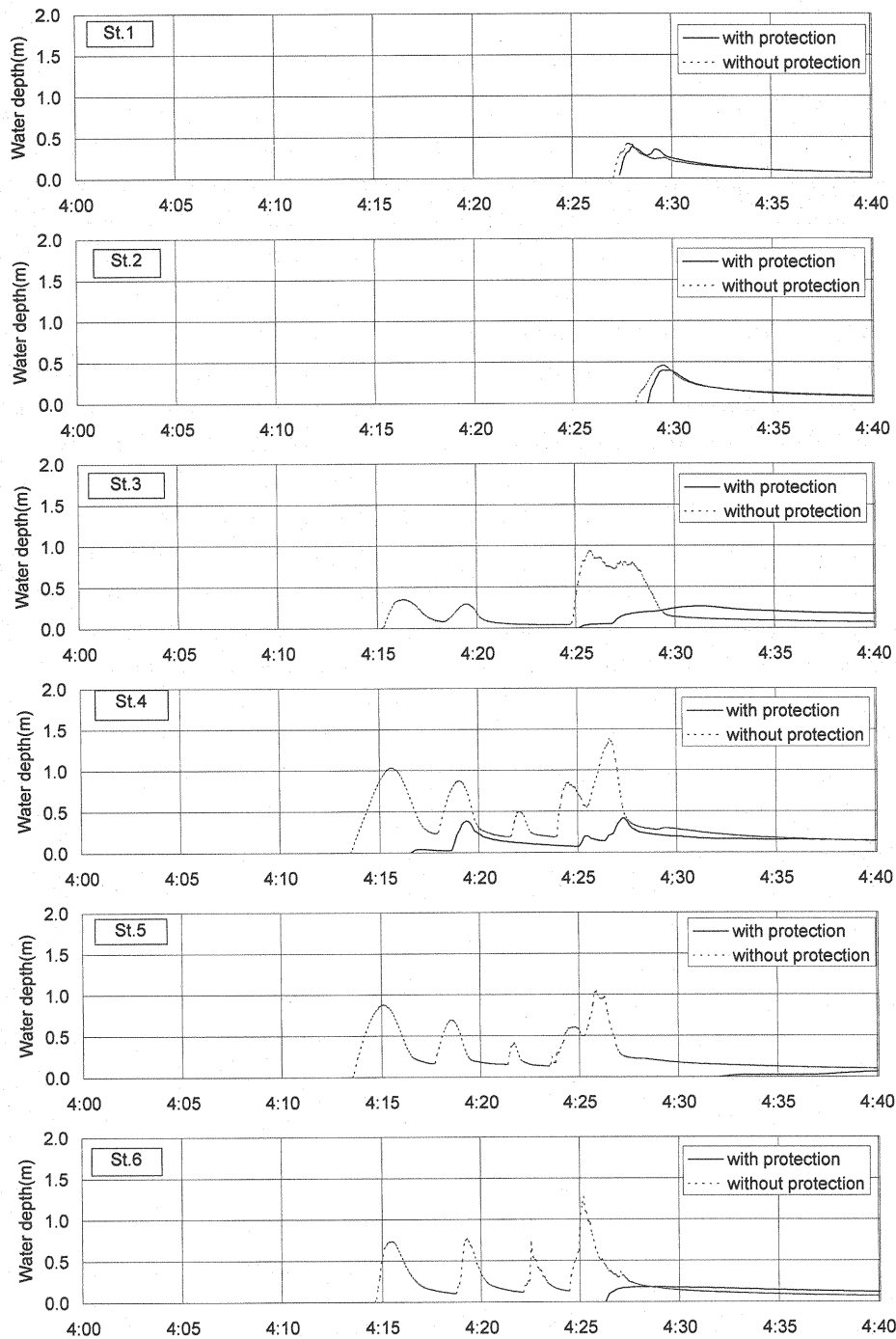
Fig.13 Comparisons of the inundation depths with and without seawalls
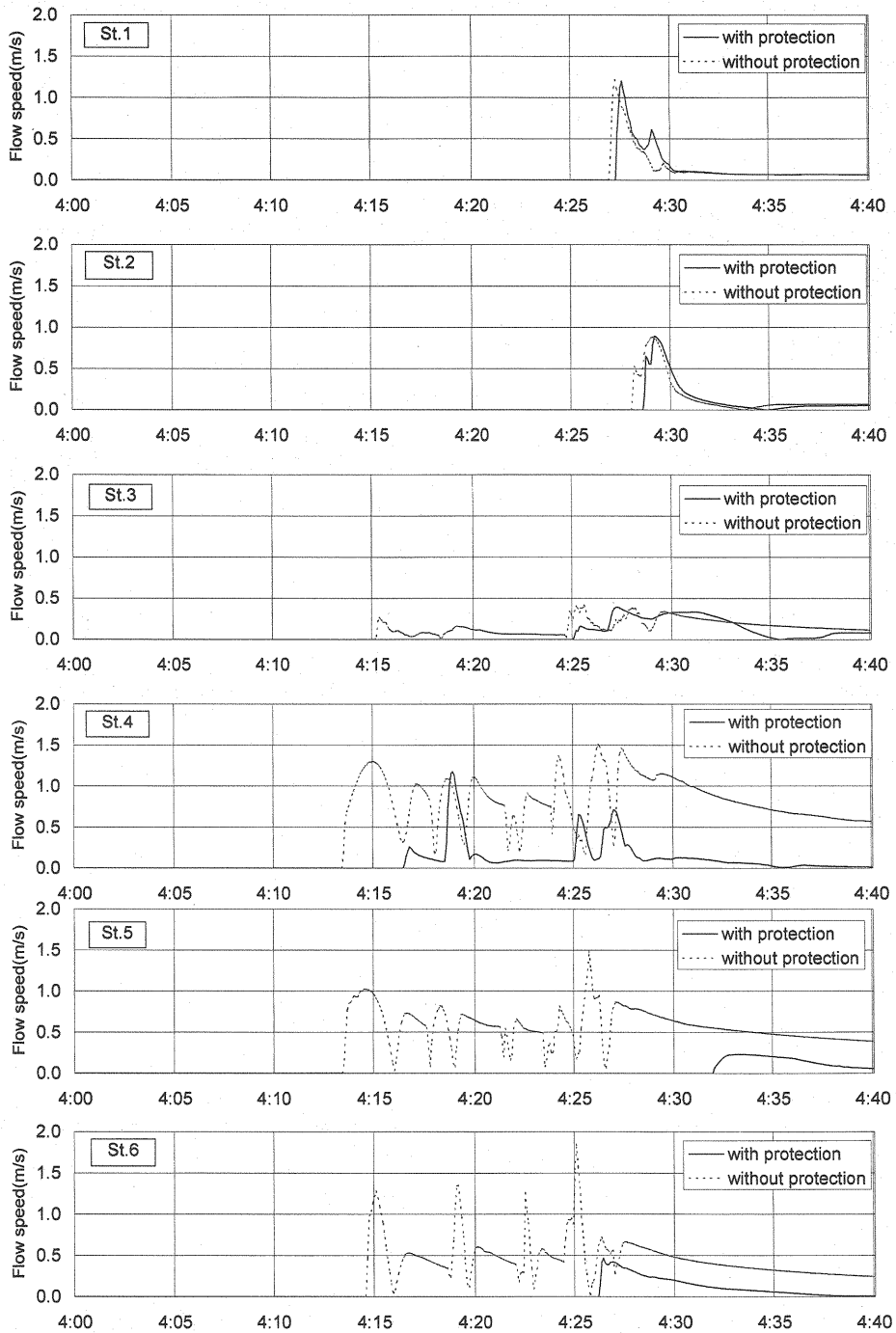
(The locations are indicated in Fig.12)

Fig.14   Comparisons of the flow speed with and without seawalls

(The locations are indicated in Fig.12)

CONCLUSION

The tsunami simulation on Male' Island yielded fairly reliable results in terms of wave propagation and inundation. The calculation results of the inundation showed that the seawalls helped to reduce the inundation area and the flow velocity on land. In general, the fluid energy is proportional to the second power of the flow velocity and the water depth. Therefore, we conclude that the reduction of the flow velocity by the seawalls mitigated damages on population and infrastructures in Male' Island.

Shore protection structures, including seawalls, play a role in reducing the tsunami inundation to a certain extent. In addition, these facilities are very effective in preventing, reducing the damage caused by tsunamis, especially in lowlands and highly populated areas such as Male' island. However, it should be noted that the facilities might work well just because the tsunami height at Male' Island was relatively small, at most 2m. For larger tsunamis, the effects of the shore protection facilities would become smaller. Therefore, it is essential to build a comprehensive prevention system including non-constructive methods such as tsunami forecasts, warning, and an evacuation guiding system in preparation for larger scale tsunamis.

ACKNOWLEDGEMNTS

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