Tsunami Due to the Tokachi-Oki Earthquake in 2003

by

Takashi Tomita[1], Hiroyasu Kawai[2] and Taro Kakinuma[3]

ABSTRACT

The Tokachi-Oki Earthquake in 2003 generated a series of tsunamis. The tsunamis struck the Pacific coasts in the Hokkaido and Tohoku regions and caused coastal flood in low-lying areas, resulting in containers and cars floated, especially in the Hokkaido region. There was, however, little serious damage of port facilities by tsunami attack. This paper described tsunami run-up and damage obtained by field investigation conducted by the Port and Airport Research Institute. The characteristics of the tsunami were also presented here, based on the tsunami measurements and numerical simulations.

KEYWORDS: Field Investigation, Numerical Simulation, Observation, Tokachi-oki Earthquake in 2003, Tsunami, Tsunami Run-up

1. INTRODUCTION

A strong earthquake whose magnitude, Mw, was 8.0, occurred around 4:50 on September 26 (JST). The epicenter of the earthquake, which was reported by the Japan Meteorological Agency (JMA), was at a depth of approximately 42km away from the Cape Erimo to east-southeast about 80km, offshore of Tokachi, south of Hokkaido, Japan (41.8N, 144.1E). The JMA named this earthquake the Tokachi-Oki Earthquake in 2003.

This earthquake generated a series of tsunamis. The tsunamis struck the Pacific coasts in the Hokkaido and Tohoku regions and caused coastal flood in low-lying areas, resulting in containers and cars floating and missing of two people, especially in the Hokkaido region. There was, however, little serious damage of port facilities by the tsunami attack.

Immediately after this earthquake, the Port and Airport Research Institute (PARI) dispatched field investigation teams to the southeast coast in the Hokkaido. The Storm Surge and Tsunami Division of PARI investigated the characteristics of tsunami run-up and damage, mainly in port and harbor areas.

This report described the tsunami run-up obtained from the field investigation and the characteristics of the tsunami based on the numerical simulations. Finally, we summarized the future study for more detailed estimation of tsunami damage.

2. TSUNAMI MEASUREMENT

JMA, Geographical Survey Institute (GSI), and Hokkaido Development Bureau of the Ministry of Land, Infrastructure and Transport (MLIT) have installed many tide observation stations along the coasts in the Hokkaido and Tohoku regions. MLIT also has set up offshore wave observation stations composing the Nationwide Ocean Wave Information Network for Port and Harbors (NOWPHAS). Some wave stations, for instance, the Off-Tokachi wave station in the offshore of the Tokachi coast, measure horizontal currents as well as water level, using a Doppler-type current meter.

Nagai et al. [1] analyzed tide data at 23 stations and wave data at 10 stations, and picked up a tsunami profile at each station. Their data showed the following tsunami features:

1) The first tsunami was measured earliest at the Off-Tokachi wave observation station at 4:51. The maximum tsunami height in the offshore of the Tokachi coast appeared at 6:42 in the fourth tsunami

---

[1] Head, Storm Surge and Tsunami Division, Marine Environment and Engineering Department, Port and Airport Research Institute, Yokosuka, 239-0826 Japan.

[2] Senior Researcher, Marine Environment and Engineering Department, Port and Airport Research Institute, ditto.

[3] Researcher, Storm Surge and Tsunami Division, Marine Environment and Engineering Department, Port and Airport Research Institute, ditto.

wave.

2) At the tide station of Tokachi Port and other 4 stations, the maximum tsunami height appeared in the first tsunami wave.
3) The tsunami heights more than 1m were observed at 6 stations among 33 stations: the Tokachi Port (2.56m), Kuji Port (1.75m), Kiritappu (1.24m), Kushiro Port (1.22m), offshore of Tokachi coast (1.18m), Akkeshi (1.02m).

The tsunami data which Nagai et al. analyzed can be downloaded from the following home page of PARI:

http://www.pari.go.jp/bsh/ky-skb/kaisho/eng/marine_home_e.htm.

3. FIELD INVESTIGATION

3.1 Outline of Field Investigation

After the earthquake, PARI judged that field investigation concerning the earthquake and tsunami damage was possible from information on the earthquake disasters, and dispatched investigation teams immediately in Hokkaido. The Storm Surge and Tsunami Division of PARI carried out tsunami investigation. In the field investigation on the tsunamis, we heard the tsunami damage and the presence of tsunami data from harbor construction offices of the Hokkaido Development Bureau. We also heard the tsunami-coming situation from residents and fishermen. In addition, we measured the height of tsunami signs based on the sea level when measuring them with a hand level and measurement pole. The height of the signs was converted into the Tokyo Peil (T.P.), which is the datum level in the altitude in Japan, using the estimated tidal levels which were calculated in terms of the tidal harmonic constants at the tidal observation stations being the nearest from the investigation points by the Japan Coast Guard.

Since the tsunami damage such as inundation was reported in ports before the field investigation, we decided to conduct the field investigation mainly at the Urakawa Port, Tokachi Port, Otsu Fishery Port, Kushiro Port, as shown in Fig. 1. However, this report introduces the tsunami run-up height in the Tokachi Port, Otsu Fishery Port and Kushiro Port, where the tsunami signs were found clearly.

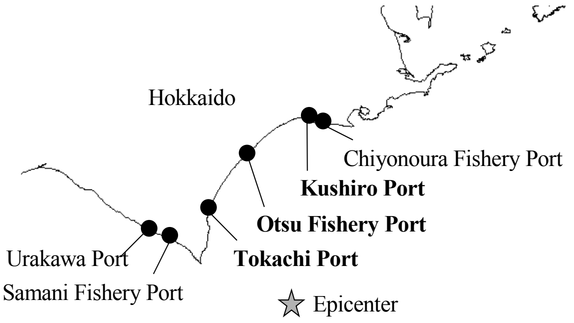


Figure 1. Points of Field Investigation on Tsunamis

As for generally saying, the tsunami attack is not so severe in the inside of ports and harbors, resulting from protection by breakwaters. Tanimoto et al. [2] showed that the tsunami run-up height in the inside of ports was lower than that of the outside of ports, based on the case in the Nihonkai Chubu Earthquake Tsunami in 1983. For the Hokkaido Nansei-Oki Earthquake in 1993, the highest tsunami run-up was measured at a local beach like a pocket beach [3, 4]. Therefore, the investigation in the outside of ports is also important to understand the characteristics of tsunamis. At this time, the tsunami run-up heights more than 4m were found at the local beaches: a east coast of the Cape Erimo and the Akkeshi coast.

3.2 Tokachi Port

Figure 2 shows the tsunami run-up height in the Tokachi Port. At the tidal observation station in the port, the maximum tsunami height of 2.53m was measured at 5:24.

Sand and mud remained on the land in the port, and these indicated the tsunami flooding. The tsunami inundation mark also remained on the wall of a cargo house which was behind the third wharf of the port (Pict. 1). The height of the mark was T.P.+2.90m, which was 0.65m on the ground. Its height was also 2.66m higher than the estimated astronomical tide, which was almost the same as the observed tsunami height at the tidal observation station. As a testimony of a person in another company office near the cargo house, inundation height was about 10 cm and more on the floor of the office. The height was almost the same as the tsunami mark at the

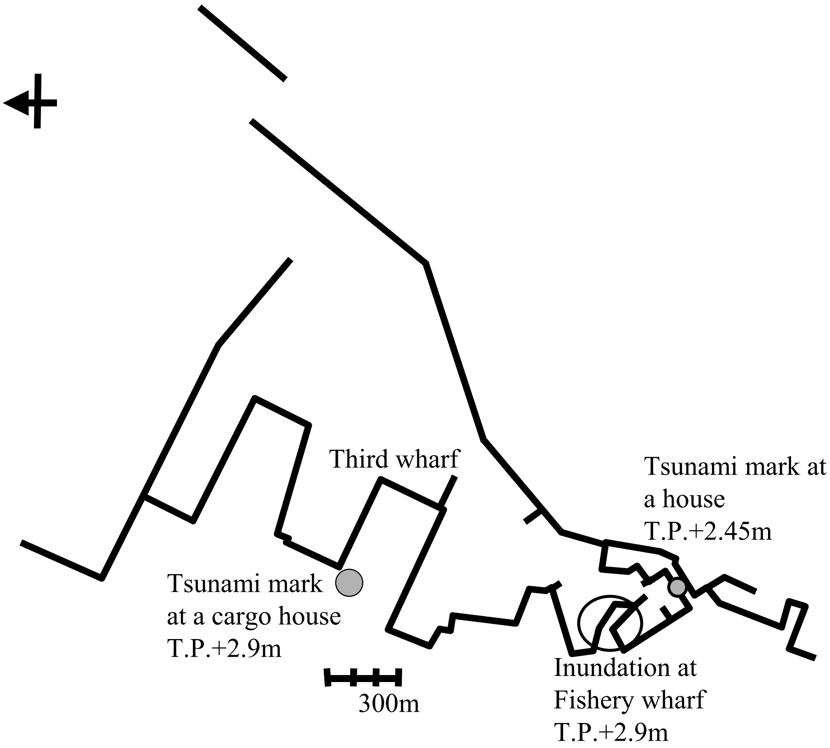
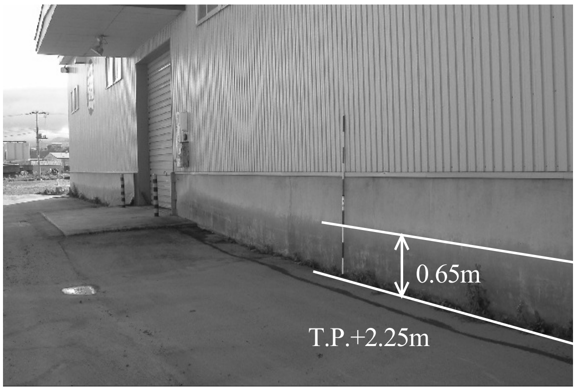


Figure 2. Tsunami Run-up Height in the Tokachi Port



Picture 1. Tsunami Inundation Mark at a Cargo House in the Tokachi Port

Picture 2. Tsunami Flood at the Fishery Wharf in the Tokachi Port (by the Hiroo Office of the Japan Coast Guard)

cargo house.

Picture 2 was taken by the Hiroo Office of the Japan Coast Guard, and shows a situation of the tsunami flood at the fishery wharf in the Tokachi Port. Judging from the photograph, the inundation height is about 1m on the ground, which is T.P.+2.9m.

In the interior area of the Tokachi Port, tsunami inundation signs remained on walls of a house. The height of the signs was T.P.+2.55m, which was 0.17m on the floor of the house (Pict. 3). This height was lower by 0.4m than the inundation height at the third wharf. The low run-up height can result from reduction of tsunami power at the narrow water area formed by existence of the fishery wharf in front of the interior of the port, as shown in Fig. 2. According to the story of the woman who stayed

Picture 3. Inundation Mark at a House in the Interior Area of the Tokachi Port

at the house at the time of the tsunami attack, the tsunami came from both of the main port, which was in front of the house, and the outer port, which was behind the house. Although a seawall behind the house protected it, the tsunami passed an opening of the seawall, which connected the main port and outer port.

At the time of our investigation in the Tokachi Port, three cars which fell into the sea due to tsunami flooding were looked for in the fishery area. According to a person concerned it, the cars moved somewhere from the places where they fell. This means that the tsunami flow cannot be ignored even in the inside of ports.

3.3 Otsu Fishery Port

Figure 3 shows the tsunami run-up height in the Otsu Fishery Port. At 4.5km offshoreward from the Otsu Fishery Port, in which the water depth is 23m, there is a wave observation station by the Hokkaido Development Bureau, MLIT. The tsunami was observed there. According to the tsunami data, the first tsunami came at 4:51 such as an ebb tide, and the maximum water level of the first tsunami was 100cm and it appeared at 5:14.

In the interior of the Otsu Fishery Port, there was a slope of 1/10 to land fishing boats and to take them down to the sea. Many boats were put on the land beyond the slope, and the tsunami flood washed away them. The tsunami run-up marks remained on walls of a house and cargo box near them. The height of them was T.P.+3.15 - 3.25m (Pict. 4). In the bush beyond the ship-putting place, a green reed was caught on a tree (Pict. 5), and a plastic bag and rope on

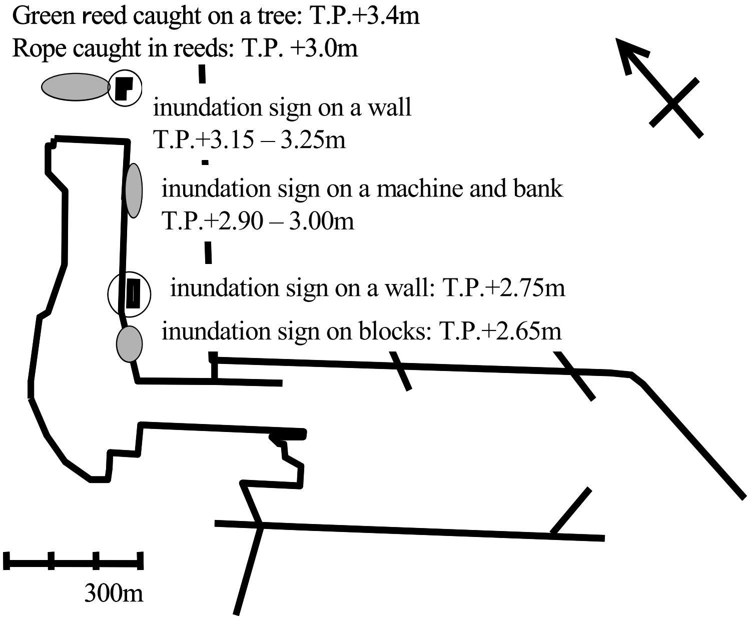


Figure 3. Tsunami Run-up Height in the Otsu Fishery Port

Picture 4. Tsunami Run-up Sign in the Interior of the Otsu Fishery Port

Picture 5. Green Reed on a Tree in the Interior of the Otsu Fishery Port

the reeds. These tsunami run-up signs don't indicate the maximum run-up height necessarily, but shows that the seawater came up to these levels at least. The height of the reed on the tree was T.P.+3.4m, which was the maximum run-up height that we found in the Otsu Fishery Port.

The tsunami run-up height was decreased, leaving the interior area in the port. On some blocks in a bending part (Fig. 3) which is close to the mouth of the port, tsunami inundation marks remained and their height were T.P.+2.65m (Pict. 6).

Picture 6. Inundation Sign on the Blocks in the Bending Part of the Otsu Fishery Port

Estimating tsunami height in the Otsu Fishery Port from these tsunami signs, it is 2.9 - 3.1m in the interior area of the port, and it decreases gradually as leaving the interior, and then 2.4m at the bending part near the mouth of the port.

3.4 Kushiro Port

Figure 4 shows the tsunami run-up height in the Kushiro Port. In the Kushiro Port, the maximum tsunami height of 1.2m was observed at 9:03 at the tide observation station, and the maximum sea level including the astronomical tide appeared at 14:22, when it was near the time of the high tide.

In the west port of the Kushiro Port, we couldn't find the tsunami run-up signs. It seems that the tsunami flood was not severe in the west port, because the wharf height was high enough to mitigate the tsunami run-up. According to the story of a worker on the second wharf, the tsunami climbed the wharf to its top. The height of an inundation edge was 0.2m on the wharf and T.P.+2.00m as a result of measurement.

In the interior area of the east port of the Kushiro Port, the tsunami overflowed to a neighboring road of the port. The height of the wharf was T.P.+0.95m, and we found tsunami run-up signs on drums and a refrigerator. The run-up height was T.P.+1.60 - 1.65m, which corresponded to 0.7m on the ground. On the opposite side beyond a small water area, there was a line of inundation marks on the walls of warehouses on the wharf, as shown in Pict. 7.

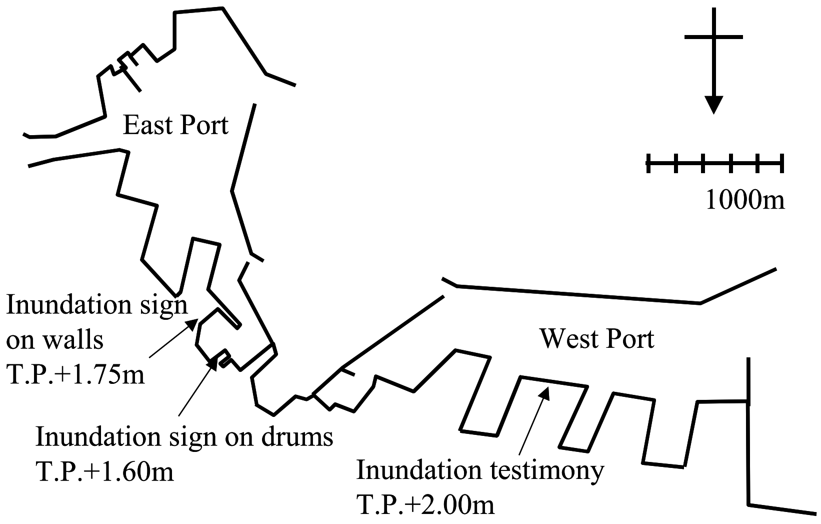


Figure 4. Tsunami Run-up Height in the Kushiro Port

Picture 7. Tsunami Inundation Sign on the Wall of the Warehouse in the East Port of the Kushiro Port

The run-up height was T.P.+1.75m, and 0.5m on the ground. If the tsunami flood occurred at the time of the high tide, the tsunami height was 1.4m in the west port and 1.0m in the interior of the east port.

4. NUMERICAL SIMULATION

4.1 Numerical Model

The numerical model used for our numerical simulations was based on the governing equations consisting of the horizontally two-dimensional non-linear shallow-water equations and continuity equation [5]:

- Continuity equation

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

- Equations of motion

$$\frac{\partial M}{\partial t}+\frac{\partial}{\partial x}\left(\frac{M^2}{D}\right)+\frac{\partial}{\partial x}\left(\frac{MN}{D}\right) =-gD\frac{\partial \eta}{\partial x}-\frac{f}{D^2}M\sqrt{M^2+N^2} \tag{2}$$

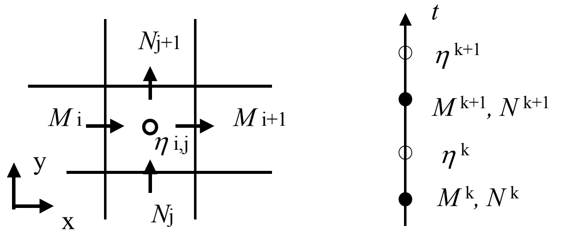
$$\frac{\partial N}{\partial t}+\frac{\partial}{\partial x}\left(\frac{MN}{D}\right)+\frac{\partial}{\partial x}\left(\frac{N^2}{D}\right) =-gD\frac{\partial \eta}{\partial y}-\frac{f}{D^2}N\sqrt{M^2+N^2} \tag{3}$$

in which

$$M=Du,\quad N=Dv,\quad D=h+\eta \tag{4}$$

x and y were the horizontal coordinates, u and v the horizontal velocities in the x and y directions, M and N the discharge fluxes in the x and y directions, h the water depth, η the water surface profile, D the total depth, g the gravitational acceleration, f the bottom friction factor, and t the time.

These equations were discretized by the finite difference method with the leap-frog method in time and the staggard mesh in space, as shown in Fig. 5.



Staggard Mesh Leap-frog Method

Figure 5. Definition Points of Variables

4.2 Water Depth Data

The water depth data in a 500m grid system by the Japan Oceanographic Data Center (JODC) [6] was used for the simulations. The data was converted in a 600m grid system (Fig. 6). Using 600m grids, we can understand tsunami features in the wide area, but cannot consider the characteristics of the tsunami in local areas such as the inside of ports. It is, therefore, necessary to use a finer grid system for discussion on the local characteristics of the tsunami in detail.

4.3 Boundary Conditions

The walls of the infinite height were supposed along coastal lines. Thus, the inundation to the land wasn't being taken into consideration.

We needed to reduce the wave reflection at the outer boundaries in the computational domain in order to avoid disturbance due to reflected waves, because we had to compute tsunamis for a long time. The simulation model had no reflection boundary conditions based on the method of characteristics [7], which could produce no reflection from outgoing waves at the boundaries

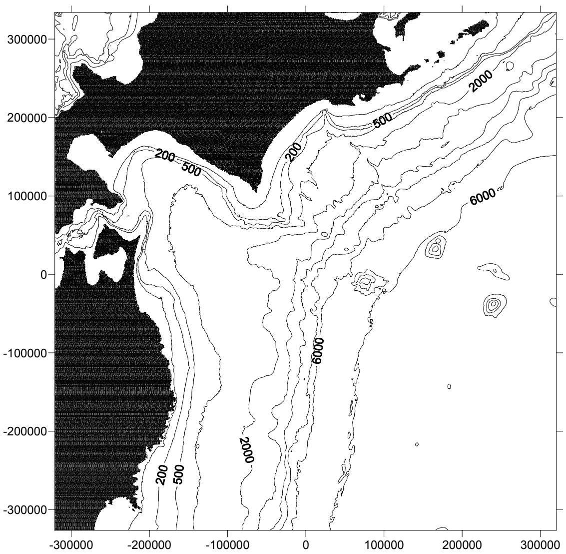


Figure 6. Water Depth Map Used in the Numerical Simulations

4.4 Fault Model

The fault models by Yamanaka and Kikuchi [8] and GSI [9] were adapted for the tsunami simulations. The fault parameters in the models are listed in Table 1. Using these fault models, the deformation of seabed was calculated with the method by Manshinha and Smylie [10], and the same deformation was given in the sea surface as the initial tsunami form (Fig. 7).

4.5 Comparison with Observed Tsunami Profiles

Figure 8 shows the tsunami profiles observed [1] and computed by the faults models. In the figure, OBS indicates the observed one, GSI the numerical results by the GSI fault model, and Y&K the numerical results by the fault model by Yamanaka and Kikuchi. The origin of the horizontal axis is the time of the earthquake occurrence of 4:50.

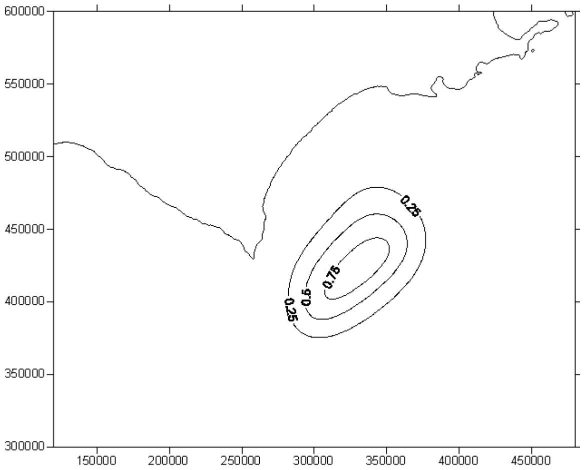
In the east side of the Cape Erimo,

- at Akkeshi, Y&K is almost agreement with OBS and GIS is a little larger than OBS,
- at the offshore of Tokashi, GIS is also larger by 1.5 times than OBS and Y&K is smaller than OBS
- at Tokachi, GSI is good agreement with OBS and Y&K is smaller than OBS.

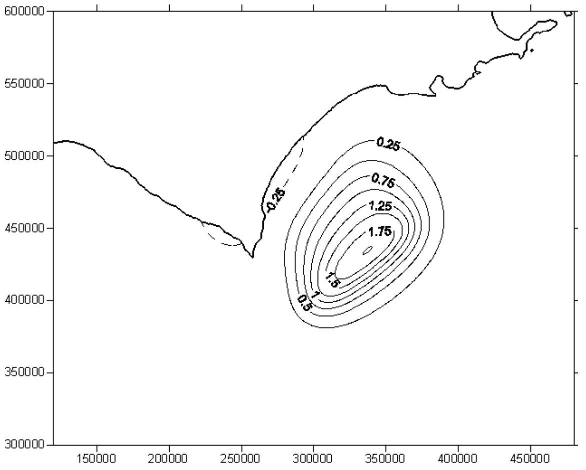
At the offshore of Tomakomai in the west side of the Cape Erimo, both of Y&K and GSI are

Table 1. Fault Parameters

Fault Model	Yamanaka & Kikuchi	GSI
Epicenter	41.78N	42.12N
(deg)	144.079E	144.55E
Length (km)	90	85.7
Width (km)	70	83
Depth (km)	25	19.7
Strike (deg)	230	231
Dip (deg)	20	21
Slip (deg)	109	110
Dislocation (m)	2.6 (mean)	5.19



(a) Yamanaka and Kikuchi



(b) GSI

Figure 7. Initial Tsunami Form by the Fault Models

good agreement with OBS. Especially, the numerical results can estimate the appearance of the maximum tsunami after 200 minutes from the earthquake occurrence. Along the coasts of the Tohoku region, Y&K is better than GSI in comparison with OBS, except for Muroran and Sendai New Port. Judging roughly from the above comparison, the fault model with large slip is better around Tokachi near the epicenter, and the fault model adapted the mean slip is better along the Tohoku region far from the epicenter, though it isn't easy to say which fault model is good to estimate the observed tsunami. Especially, the computation in the fine grids is necessary to reproduce the tsunami in the inside of ports.

In the Kushiro Port, though the tsunami profile isn’t shown in Fig. 8, the numerical results by the GSI fault model corresponds to the observed tsunami well. The observed tsunami has the maximum level of 1.22 at 9:06, and the maximum tsunami level in the numerical result is 1.55m at 9:05. Another high tsunami level of 1m is observed at 14:22, and the numerical tsunami has the extreme value of 0.8m at 14:22.

4.6 Comparison About Velocity

Figure 9 indicates the observed and computed horizontal velocities near the water surface at the offshore of Tokachi. It should be noted here that the north direction of the observed data is turned to the west direction at 40 degrees for the purpose of corresponding to the directions of the computed and observed velocity vectors. Because Nagai and Ogawa [11] pointed out that there was a difference of 10cm in the water level data before and after the earthquake, resulting from subsidence of the seabed or the measuring instrument. If the seabed or measuring instrument sinks, the possibility that the direction of the instrument is changed cannot be denied. However, we must wait for the future investigation whether the instrument rotates.

In Fig. 9 the computed velocities are good agreement with the observed one as well as the water surface fluctuation. The east-west velocity component (X-Vel. in the figure) is strong until about 150 minutes, and the north-south velocity component (Y-Vel.) begins to appear from about 100 minutes. This velocity feature indicates that the tsunami attacked from the east firstly. Then, it propagated along the coastal line of the Tokachi coast as edge waves, resulting from the influence of bathymetry around the Southeast of Hokkaido.

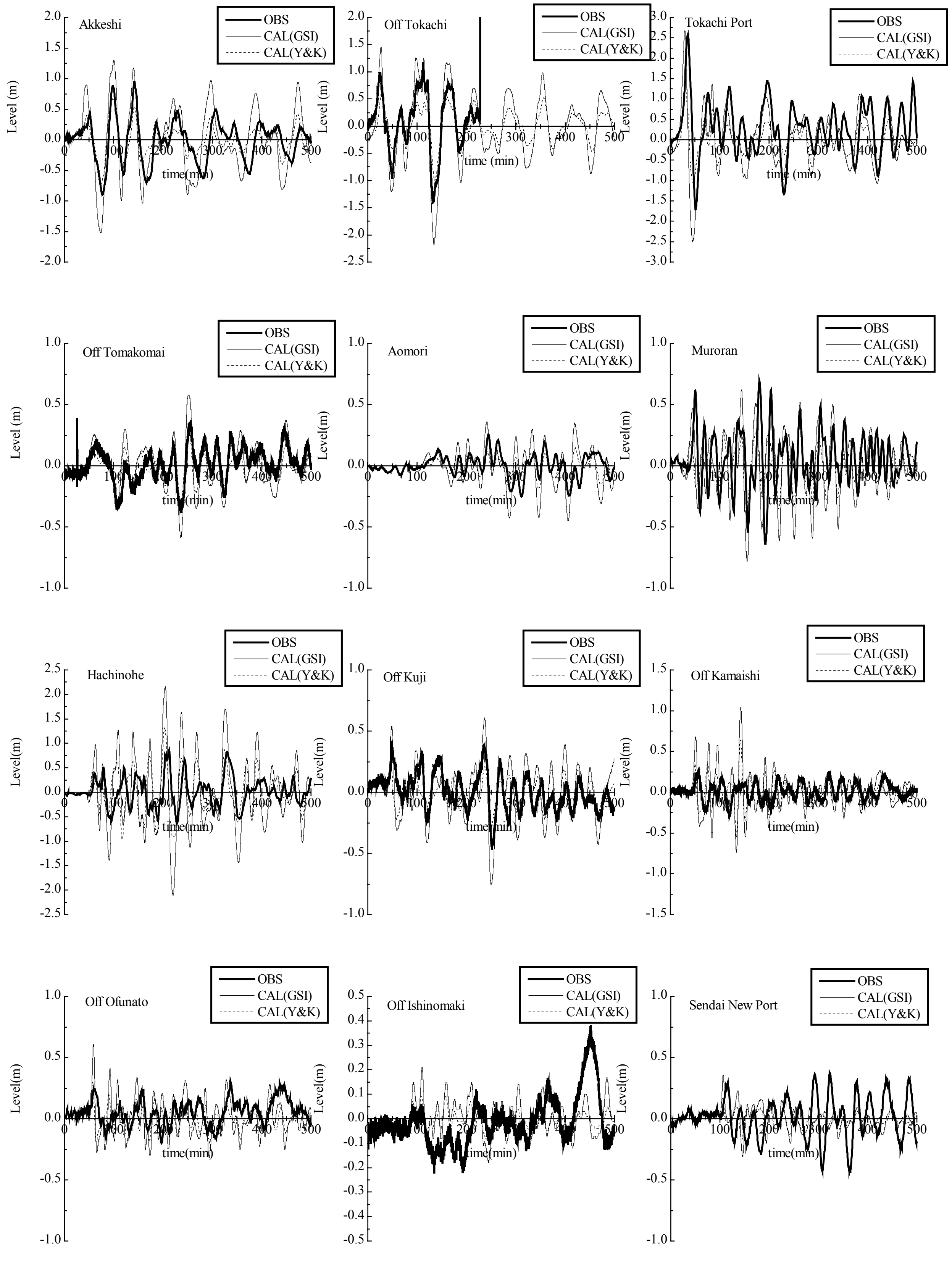


Figure 8. Observed and Computed Tsunami Profiles

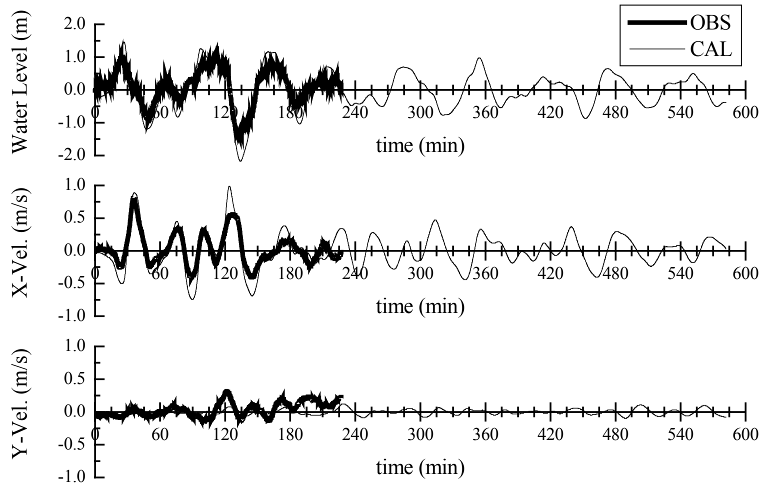
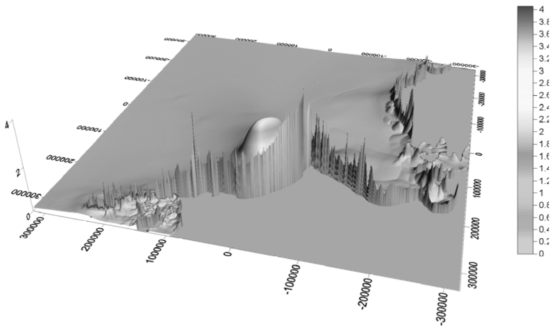
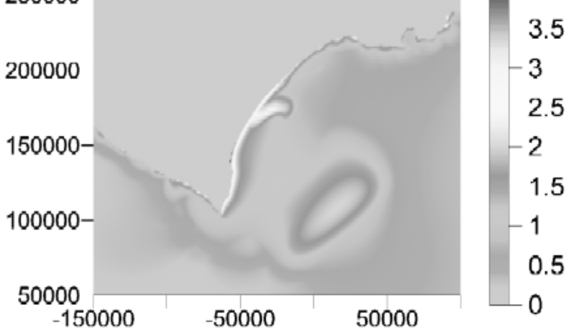


Figure 9. Water Surface and Horizontal Velocities in the Offshore of the Tokachi Coast



(a) Bird's Eye View of All Computational Domain



(b) Plane View of Southeastern Hokkaido

Figure 10. Maximum Tsunami Height

4.7 Maximum Tsunami Height

Figure 10 shows the distribution of the maximum tsunami height. The tsunami has high level more than 3m in the east coast of the Cape Erimo. Around Hyakunin-hama where an investigation team of Hokkaido University found the tsunami run-up reaching to T.P.+4m in the east side of the Cape Erimo, the computed height is 2.8m, even though local topography around there isn't reproduced in the numerical simulation. There is an area where the maximum tsunami height is high in the offshore of the Tokachi coast. The time when the maximum tsunami height appears is late in comparison with the neighboring area. It appears in 200 minutes after the earthquake occurrence, and this time corresponds to the time when the north-south velocity component appears. These relations mean the edge waves responsible for the maximum tsunami height in the offshore area.

4.8 Tsunami Arrival Time

Table 2 shows the tsunami arrival time at each observation station. The numerical results by the GSI fault model are listed in the table, and they are good agreement with the observation results, except for Kiritappu and Akkeshi. For the observation results, some reasons are necessary to explain that the tsunami arrives at Kiritappu earlier than at Akkeshi, because Kiritappu is more far from the epicenter than Akkeshi.

Table 2. Tsunami Arrival Time

Point	Observation	GSI fault model
Kiritappu	5 min.	28 min.
Akkeshi	14 - 18	26
Kushiro	13	10
Off Tokachi	1	less than 1
Off Tomakomai	47	46
Off Kuji	41	39
Off Kamaishi	35	43
Off Ofunato	46	49
Off Ishinomaki	88	85

5. SUMMARY

The tsunami due to the Tokachi-oki Earthquake in 2003 was big since the Hokkaido Nansei-oki Earthquake Tsunami in 1993. The tsunami run-up was high in the Tokachi coast, and the tsunami reached up to about 3m. Especially the run-up height was 4m in the east coast of the Cape Erimo. On the other hand, it was about 2m in the south coast of the eastern Hokkaido where the high run-up was recorded by the Tokachi-oki earthquake tsunami in 1952. The local topography brings high run-up of 4m in the coast of Akkeshi.

It is a feature of this tsunami that the tsunami attack continued for a long time. This is because energy of the tsunami was trapped in the Tokachi coast whose geographical form was like a bow. The characteristics of the tsunami in the wide area could be evaluated by means of the numerical simulations which used the horizontally 2D numerical model, the 600m grid system and the uniform slip fault models by Yamanaka and Kikuchi and GSI. However, the numerical simulations in this study cannot evaluate the tsunami in detail in the inside of ports and around complicated topography. Therefore, the detailed computation including the tsunami flood on the land will be left as a future investigation.

It was at this time shown that the offshore wave observation in front of an objective coast could sense tsunami on the coast several minutes before the actual tsunami attack. When the Irianjaya Earthquake Tsunami in 1996 attacked Japan, the offshore wave observation at an island which located in front of the mouth of Tokyo Bay caught the tsunami 30 minutes earlier than the observation at the bay mouth [12] in the same way as this time. These show the possibility of a real-time tsunami warning based on the observation data.

6. REFFERENCES

1. Nagai, T. et al.: Characteristics of the Observed 2003 Tokachi-Off Earthquake Tsunami Profile, *Coastal Engineering Journal*, 2004 (submitted. in Japanese).
2. Tanimoto, K., et al.: Field and Laboratory Investigations of the Tsunami Caused by 1983 Nihonkai Chubu Earthquake, *Tech. Note of PHRI*, No. 470, 1983 (in Japanese).
3. Shuto, N. et al.: *Proc. Coastal Eng, JSCE*, Vol. 41, pp. 236 - 240, 1994 (in Japanese).
4. Takayama, T. et al.: Field Investigations of the Tsunami Caused by 1992 Hokkaido Nansei-oki Earthquake, *Tech. Note of PHRI*, No. 775, 1994 (in Japanese).
5. Goto, C and Sato, K.: Development of Tsunami Numerical Simulation System for Sanriku Coast in Japan, *Rep. of PHRI*, Vol. 32, No. 2, pp. 3 - 43, 1993 (in Japanese).
6. JODC: http://jodc.go.jp/
7. Anderson, D.A., Tannehill, J.C. and Pletcher, R.H.: Computational Fluid Mechanics and Heat Transfer, *Taylor and Francis*, 1984.
8. Yamanaka & Kikuchi: EIC Seismological Note, No. 139, 2003. (http://wwweic.eri.u-tokyo.ac.jp/EIC/EIC_News/030926e.html)
9. GSI: http://www.gsi.go.jp/
10. Mansinha, L. and Smylie, D. E.: The Displacement Ffield of Inclined Faults, *Bulletin of the Seismological Society of America*, Vol. 61, No. 5, pp. 1433-1440, 1971.
11. Nagai, T. and Ogawa: Tokachi-off Earthquake Tsunami Profile, *Tech. Note of PARI*, No. 1070, 2004 (in Japanese).
12. Kobune, K. et al.: Characteristics of the Irianjaya Earthquake Tsunami in 1996, *Tech. Note of PHRI*, No. 842, 1996 (in Japanese)