STORM SURGE IN ISE AND MIKAWA BAY CAUSED BY TYPHOON

by

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ABSTRACT

The typhoon No.15 in 1959 gave enormous storm surge disaster in Ise and Mikawa Bay in Japan. Such a strong typhoon may occur again in the future. According to the result of numerical simulation, the meteorological tide anomaly depends on the route of a typhoon, and is directly proportional to the progression speed, the pressure differential, and the radius. The mean sea level rising due to global warming may reduce the tide anomaly, but the sum of the tide anomaly and the mean sea level rising will become larger.

KEY WORDS: Isewan Typhoon
Mean Sea Level Rising
Meteorological Tide Anomaly

1. INTRODUCTION

In 1959, a terribly strong typhoon landed on the Honshu Island in Japan and gave enormous storm surge disaster especially in Ise Bay and also in Mikawa Bay. Although no large meteorological tide anomaly has been occurred since then, it may occur again in the future. Additionally, global warming may raise the mean sea level and increase the radiuses and pressure differentials of typhoons on average.

In this paper, the storm surge disaster caused by the Isewan Typhoon is introduced briefly, and the meteorological tide anomalies in the imaginary typhoons with various routes, progression speeds, pressure differentials, and radiuses are computed by a numerical model. The effect of the mean sea level rising on the tide anomaly is also discussed.

2. THE ISEWAN TYPHOON

(1) Ise and Mikawa Bay

Both Ise and Mikawa Bay are located at the central region of the Honshu Island in Japan, and face the Pacific Ocean. As shown in **Figure 1**, Ise Bay is approximately 20 km wide at the entrance from the Pacific Ocean, 60 km long to the inner end, and less than 40 m deep at the center. Mikawa Bay is approximately 10 km wide at the entrance from Ise Bay, 30 km long, and less than 20 m deep at the center.

Some sever typhoons go across the Honshu Island every year, and some of them cause large

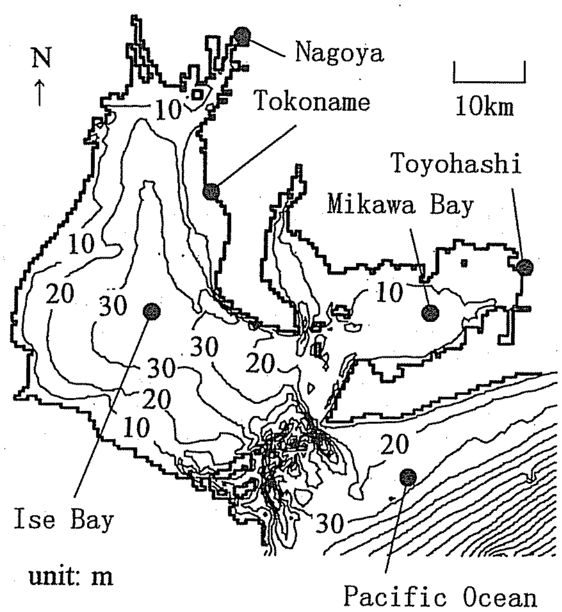

Figure 1 Topography of Ise and Mikawa Bay

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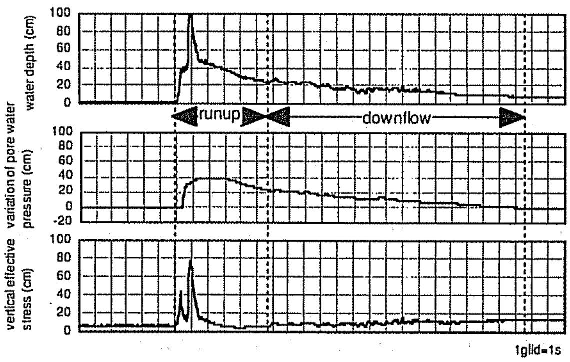


Figure 13 Water depth, pore pressure variation and vertical effective stress at the offshore point (case 2)

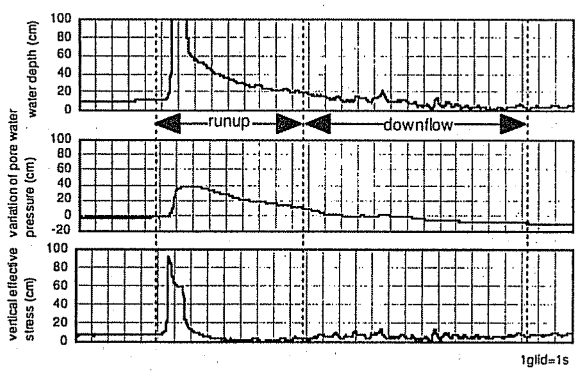


Figure 14 Water depth, pore pressure variation and vertical effective stress at the offshore point (case 3)

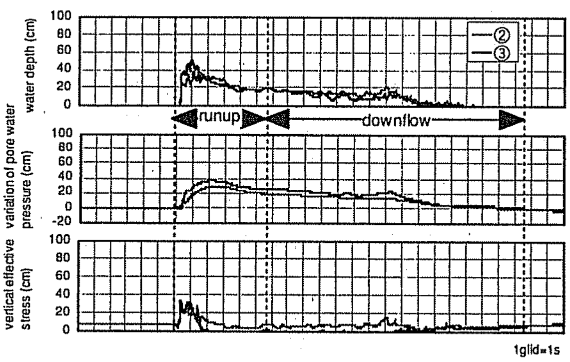


Figure 15 Water depth, pore pressure variation and vertical effective stress at the side point (case 2)

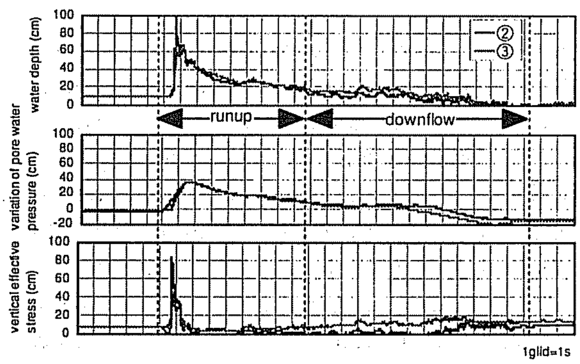


Figure 16 Water depth, pore pressure variation and vertical effective stress at the side point (case 3)

meteorological tide anomaly in the inner parts of these bays. The water depth in these bays is enough shallow to cause conspicuous storm surge easily.

(2) Storm surge disaster by the Isewan Typhoon

The typhoon No.15 landed near Shionomisaki in the Honshu Island in Japan at about 6:20 p.m. on September 26, 1959. The minimum atmospheric pressure was 929.5 hPa.

The typhoon went toward the NNE, passed the west side of Ise Bay, and caused conspicuous storm surge in Ise and Mikawa Bay. At Nagoya, located at the inner end of Ise Bay, the wind speed began to increase in the afternoon, and reached a maximum between 8:00 p.m. and 10:00 p.m. The maximum instantaneous wind velocity was 50.2 m/s. The meteorological tide anomaly of 3.45 m was also recorded there at about 9:35 p.m. The tide anomaly has been the maximum record in Japan so far.

Some coastal dikes especially in Ise Bay and also in Mikawa Bay were collapsed, and subsequently the land areas at the backward were covered with sea water. The inundation increased the damage on humans, structures, and agriculture there. According to official reports, 4,697 people were killed, 401 missing, 38,921 wounded in the typhoon. The death toll has been worst in Japan since then until now. Additionally, approximately 7,600 boats and 834,000 residential building were damaged. The typhoon was named *Isewan Typhoon*, because most damages were focused on the coast of Ise Bay. *Wan* means *bay* in Japanese.

There are several accepted opinions on why the area in Ise Bay was deadly damaged. The first one is that the meteorological tide anomaly caused by the Isewan Typhoon was extremely large. **Figure 2** shows the tide anomalies which were measured in these 43 years (from 1952 to 1994) at the tide station in the Nagoya Port by the Meteorological Agency, Japan. Applying the occurrence probability of the tide anomalies to the type II extreme distribution function, the return period of the tide anomaly due to the Isewan Typhoon becomes approximately 120 years, and the extreme tide anomaly with a return period of 50 years becomes approximately 2.5 m.

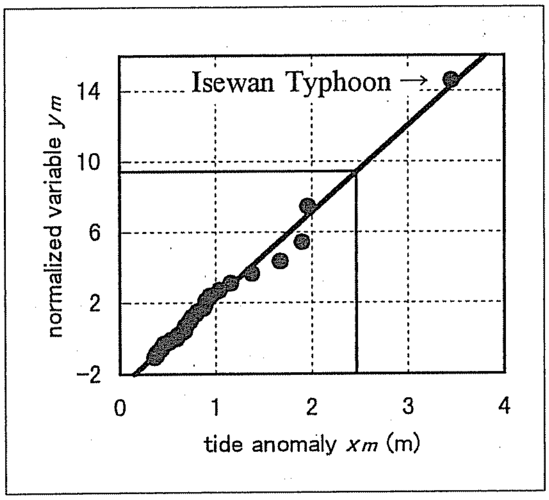


Figure 2 Occurrence distribution of extreme meteorological tide anomalies in Nagoya

The second is that the center of the Isewan Typhoon passed the west side of Ise Bay. In other words, the bay was within the dangerous semicircle of the typhoon. It will be confirmed later in the **chapter 4** by using a numerical model whether the route of the typhoon was worst for Nagoya or not.

The third is that the astronomical tidal level was higher than M.S.L. (mean sea level). The spring tidal range in autumn at Nagoya is approximately 2.3 m, but the tidal range on September 26, 1959 was less than 1.0 m and almost equal to the neap tidal range, as shown in **Figure 3**. When the meteorological tide anomaly became the maximum at around 9:35 p.m., the astronomical tidal level was only 0.2 m above the M.S.L. Assuming that the Isewan Typhoon attacked one week earlier, the high tide level was 1.1 m above the M.S.L. and the

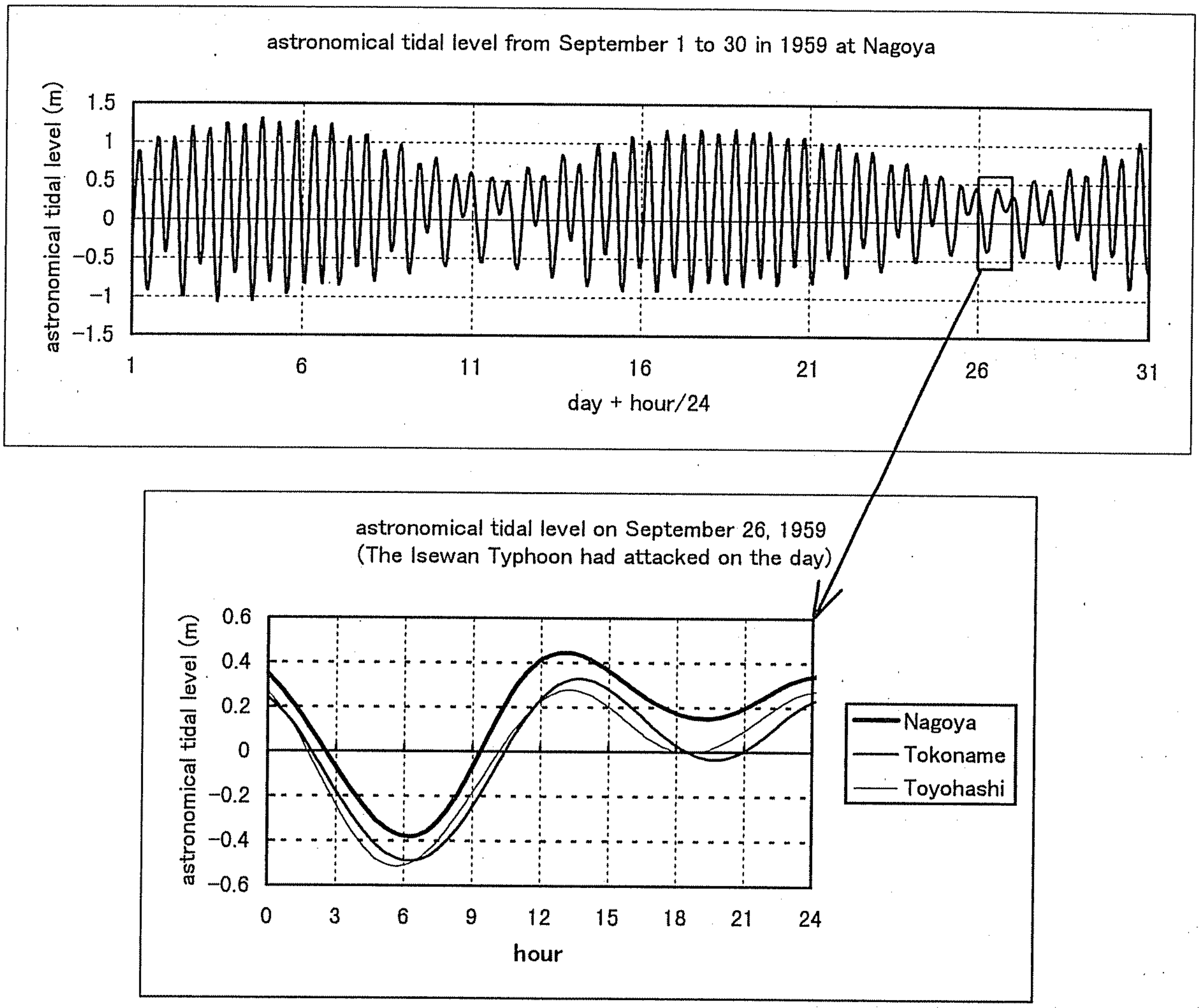


Figure 3 Profile of astronomical tidal level in September, 1959

disaster might become more enormous. The effect of tidal level on storm surge will be discussed later in the **chapter 4**.

The fourth is that much timber carried away from lumberyards in the Nagoya Port might destroy many residential building to kill many houses.

The fifth is that the Isewan Typhoon attacked at night. Electric power supply was shut down by violent winds and enormous floods, and subsequently it became hard to avoid destroyed or flooded houses and find a refuge without street lamps.

(3) Construction of storm surge breakwater

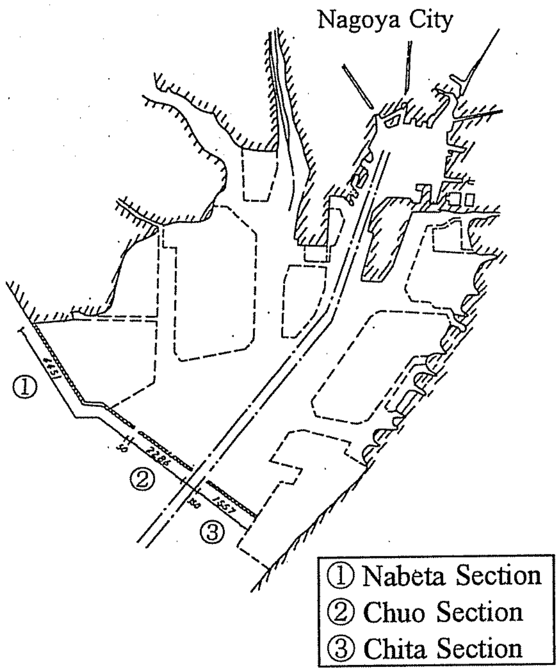
After the Isewan Typhoon had caused the disaster, a storm surge breakwater as shown in **Figure 4** was designed to mitigate the future disaster in the Nagoya Port. The breakwater consists of three sections, namely, the Nabeta Section, the Chuo Section, and the Chita Section. Their design length were 4.450, 2.285, and 1.515 km respectively. The design crest height was decided to be 4.50 m above the H.W.L. in autumn.

The following effects were expected.

(a) Reducing the peak of the meteorological tide anomaly by making the breakwater gap narrow.

(b) Preventing wind waves generated in Ise Bay from entering the Nagoya Port.

By the above two effects, it was expected that the design crest heights of quays and tide barriers at the backward of the storm surge breakwater could be low, and that the construction cost for port facilities also could be reduced totally.



(a) Layout of the storm surge breakwater

The construction of the breakwater had started in January, 1962 and finished in August, 1964. After that, the breakwater gaps had been expanded until 1968 for safe navigation. The lengths of the Nabeta Section, the Chuo Section, and the Chita Sections became 4.126, 2.136, and 1.331 km respectively. **Photo 1** shows the present condition of the breakwater. The breakwater has never damaged heavily until now, and is expected to keep its effects in the future.

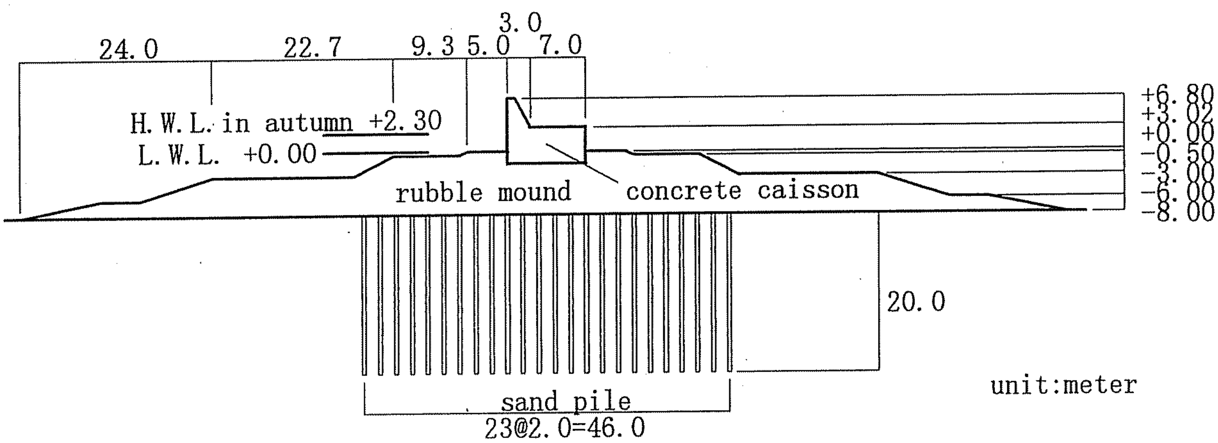
3. NUMERICAL MODEL FOR STORM SURGE

(1) Assumption for winds by typhoon

The distribution of the atmospheric pressure in a typhoon is given by the Myer's formula as follows.

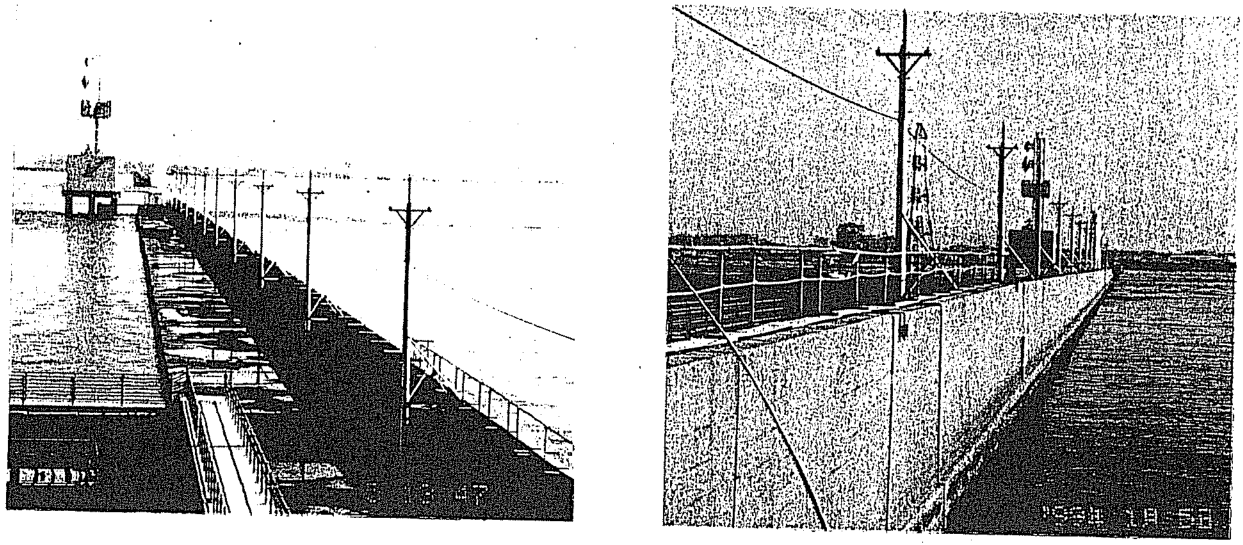
$$P = P_C + \varDelta P \cdot \exp\left(-\frac{r_0}{r}\right) \tag{1}$$

where, P is the atmospheric pressure at the point with a radial distance r from the center of a typhoon, P_c is the atmospheric pressure at the center of a typhoon, $\varDelta P$ is the pressure differential, and r_0 is the influence radius of a typhoon. Assuming the distribution shown in the above equation, the gradient wind speed U_{gr} is given as follows.



(b) Cross-section of the Chuo Section

Figure 4 Storm surge breakwater at the entrance of the Nagoya Port



(a) Rear of the storm surge breakwater (b) Front of the storm surge breakwater

Photo 1 Present condition of the storm surge breakwater

$$U_{gr}=-\frac{rf}{2}+\sqrt{\left(\frac{rf}{2}\right)^2+\frac{\Delta P}{\rho_a}\frac{r_0}{r}\exp\left(-\frac{r_0}{r}\right)} \quad (2)$$

where, f is the Coriolis coefficient, ρ_a is the density of atmosphere. The wind speed is actually reduced by the friction along sea surface. The actual wind speed, namely marine wind speed, U_1 can be assumed as follows.

$$U_1=C_1U_{gr} \quad (3)$$

where, C_1 is the parameter assumed to be 0.66 in this paper.

The movement of a typhoon also generates the winds of which speed U_2 is given as follows.

$$U_2=\frac{U_1(r)}{U_1(r_0)}V \quad (4)$$

where, V is the progression speed of a typhoon. The directions of the wind component and the typhoon progression are identical.

(2) Assumption for propagation of meteorological tidal waves

The propagation of meteorological tidal waves caused by a typhoon can be represented by long wave theory. The equation of continuity and the equations of motion can be written as follows.

$$\frac{\partial\eta}{\partial t}+\frac{\partial M}{\partial x}+\frac{\partial N}{\partial y}=0 \quad (5)$$

$$\frac{\partial M}{\partial t}+\frac{\partial}{\partial x}\left(\frac{M^2}{D}\right)+\frac{\partial}{\partial y}\left(\frac{MN}{D}\right)=+fN-gD\frac{\partial\eta}{\partial x}-\frac{D}{\rho_w}\frac{\partial p_0}{\partial x}+\frac{1}{\rho_w}(\tau_{sx}-\tau_{bx})+A_h\left(\frac{\partial^2 M}{\partial x^2}+\frac{\partial^2 M}{\partial y^2}\right) \quad (6a)$$

$$\frac{\partial N}{\partial t}+\frac{\partial}{\partial x}\left(\frac{MN}{D}\right)+\frac{\partial}{\partial y}\left(\frac{N^2}{D}\right)=-fM-gD\frac{\partial\eta}{\partial y}-\frac{D}{\rho_w}\frac{\partial p_0}{\partial y}+\frac{1}{\rho_w}(\tau_{sy}-\tau_{by})+A_h\left(\frac{\partial^2 N}{\partial x^2}+\frac{\partial^2 N}{\partial y^2}\right) \quad (6b)$$

where, t is the time, x and y axes are taken in the horizontal direction, g is the gravity acceleration, ρ_w is the density of sea water, p_0 is the atmospheric pressure on the water surface, A_h is the horizontal eddy viscosity coefficient, D is the water depth, M and N are the flux flows defined as follows.

$$D=h+\eta \quad (7)$$

$$M=\int_{-h}^{\eta}udz \quad (8a)$$

$$N=\int_{-h}^{\eta} vdz \quad (8b)$$

where, z axis is taken in the vertical direction, and $z=-h$ at the sea bottom, $z=\eta$ at the water surface. u and v are the components of the velocities in the directions of the x and y axes respectively. Additionally, τ_{sx} and τ_{sy} are the tangential stress along the water surface, and τ_{bx} and τ_{by} are the tangential stress along the sea bottom in the directions of the x and y axes respectively shown as follows.

$$\tau_{sx}=\rho_a C_D W_x \sqrt{W_x^2+W_y^2} \quad (9a)$$

$$\tau_{sy}=\rho_a C_D W_y \sqrt{W_x^2+W_y^2} \quad (9b)$$

$$\tau_{bx}=\frac{\rho_w g n^2}{D^{7/3}} M \sqrt{M^2+N^2} \quad (10a)$$

$$\tau_{by}=\frac{\rho_w g n^2}{D^{7/3}} N \sqrt{M^2+N^2} \quad (10b)$$

where, C_D is the resistance coefficient along the sea surface, W_x and W_y are the wind velocities at 10 meters above the sea surface, n is the Manning's roughness parameter.

(3) Difference method and grid mesh

In this paper, the governmental equations are solved by a difference method with a stacked grid mesh for space successive steps and the leap-frog method for time successive steps.

The five regions shown in **Table 1** are combined with each other. The first region includes a part of the Pacific Ocean around the Japan Islands, and the fifth region includes Ise and Mikawa Bay. The meteorological tidal waves is

Table 1 Grid Mesh

region	number of grid points	space interval
I	58 × 56	32.4 km
II	78 × 44	16.2 km
III	63 × 49	5.4 km
IV	81 × 78	1.8 km
V	135 × 135	0.6 km

reproduced during 24 hours, namely from 3:00 a.m. on September 26, 1959 to 3:00 a.m. on the next day. The time interval between successive steps is 0.5 s.

4. EFFECT OF VARIOUS FACTORS ON STORM SURGE

(1) Storm surge by Isewan Typhoon

Figures 5 and **6** show the profile of the atmospheric pressure, wind speed, wind direction, and meteorological tide anomaly, which are computed by the numerical model shown in the chapter 3. Nagoya and Tokoname are located in the inner part of Ise Bay, and Toyohashi in Mikawa Bay, as shown in Figure 1.

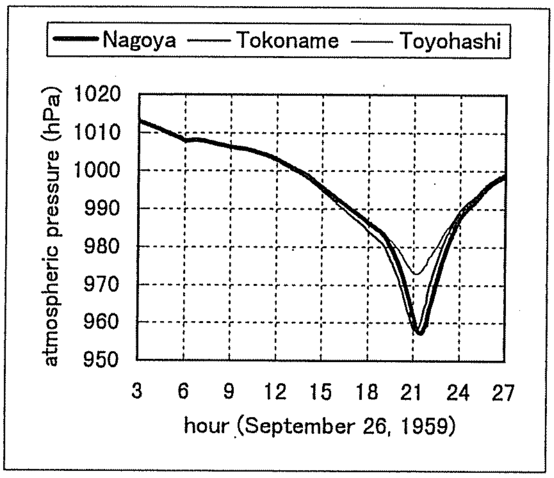
While the typhoon was approaching the Honshu Island, the wind direction was E and the wind speed was increasing to 20 m/s as shown in Figures 5 (b) and 5 (c). The meteorological tide anomaly along the west coast of Ise Bay became more than 0.5 m at 5:00 p.m. as shown in Figure 6 (a).

After the typhoon had landed on the Honshu Island at about 6:20 p.m., the wind direction changed into SE, the wind speed continued to increase, and the meteorological tide anomaly began to increase rapidly, as shown in Figure 5 (d). The meteorological tide anomaly especially along the northwest coast became large at 8:00 p.m. as shown in Figure 6 (b). The wind direction changed quickly into SW, and the meteorological tide anomaly at the inner area of Ise and Mikawa Bay became more than 3 m at 10:00 p.m. as shown in Figure 6 (c).

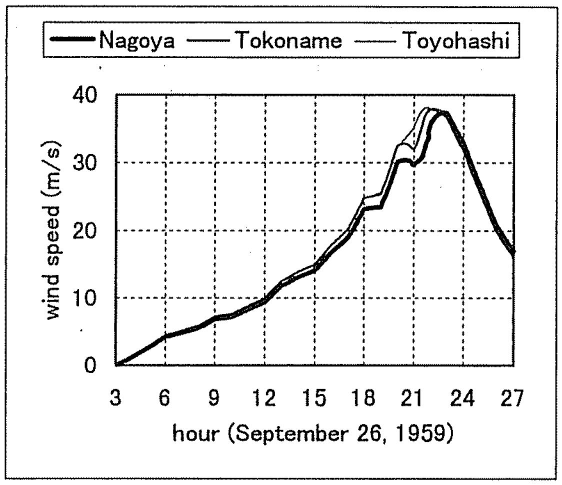
The atmospheric pressure reproduced by the numerical model reaches 957 hPa (958.5 hPa was recorded by the observation), the wind speed 37 m/s (37 m/s), and the tide anomaly 3.46 m (3.45 m) at Nagoya. The results of the numerical model and the observation get agree each other.

Figure 7 shows the distribution of the maximum meteorological tide anomaly at each place in Ise Bay and Mikawa Bay in the Isewan Typhoon. The maximum tide anomaly is larger than 1.5 m in all the area of Ise and Mikawa Bay, and larger than 3 m in the inner areas of these bays.

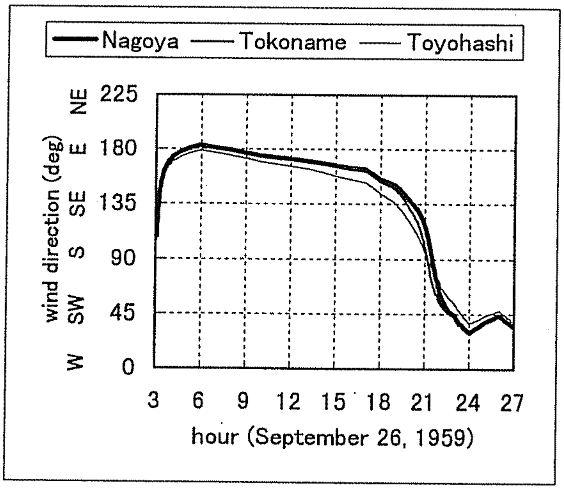
Immediately after the typhoon had passed, the meteorological tide anomaly became negative as shown in Figure 6 (d).



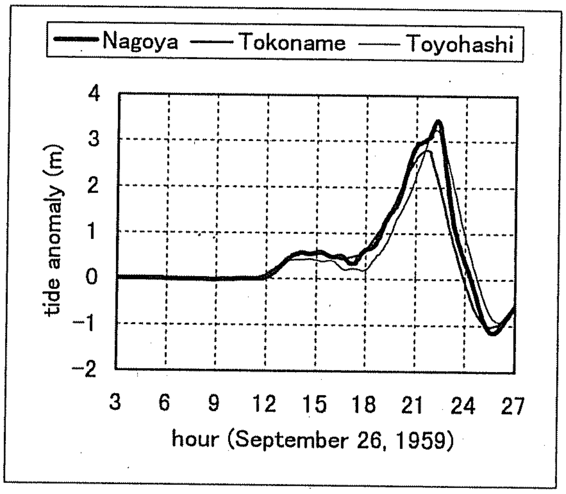
(a) Atmospheric pressure



(b) Wind speed

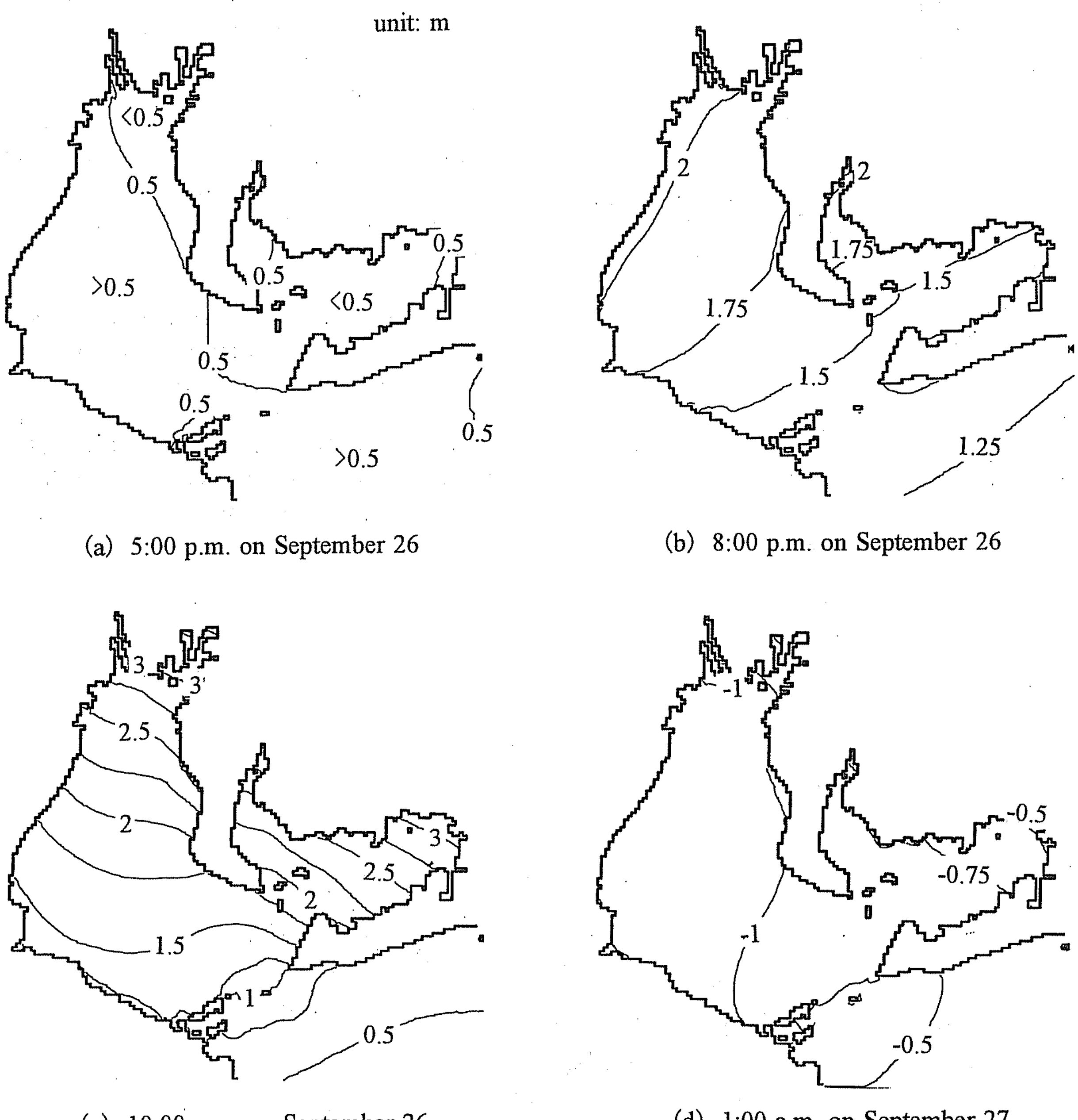


(c) Wind direction



(d) Meteorological tide anomaly

Figure 5 Profile of storm surge in the Isewan Typhoon



(a) 5:00 p.m. on September 26

(b) 8:00 p.m. on September 26

(c) 10:00 p.m. on September 26

(d) 1:00 a.m. on September 27

Figure 6 Meteorological tide anomaly in the Isewan Typhoon

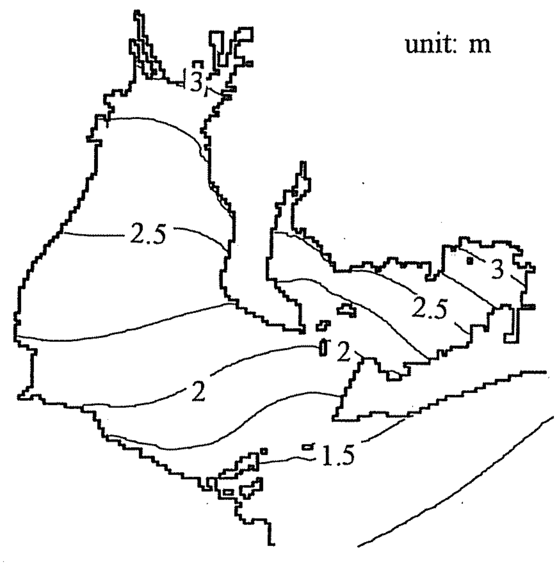


Figure 7 Distribution of Maximum Meteorological Tide Anomaly caused by the Isewan Typhoon

(2) Route of typhoon

According to an accepted opinion, the route of the Isewan Typhoon was most dangerous for the coast of Ise Bay. In this paper, the typical typhoon routes shown in **Figure 8** are assumed to estimate the effect of the typhoon route on the meteorological tide anomaly. All the imaginary routes W2, W1, and E1 to E4 are parallel to the actual route A, and the interval between one route and the next is 0.25 degree in longitude.

Figure 9 (a) shows the maximum meteorological tide anomaly for each typhoon route. The actual route gives the largest tide anomaly at Nagoya and Tokoname in Ise Bay. The tide anomalies for the routes W1 and E1, namely to the west and east by 0.25 degree from the actual route, are almost same as that for the actual route.

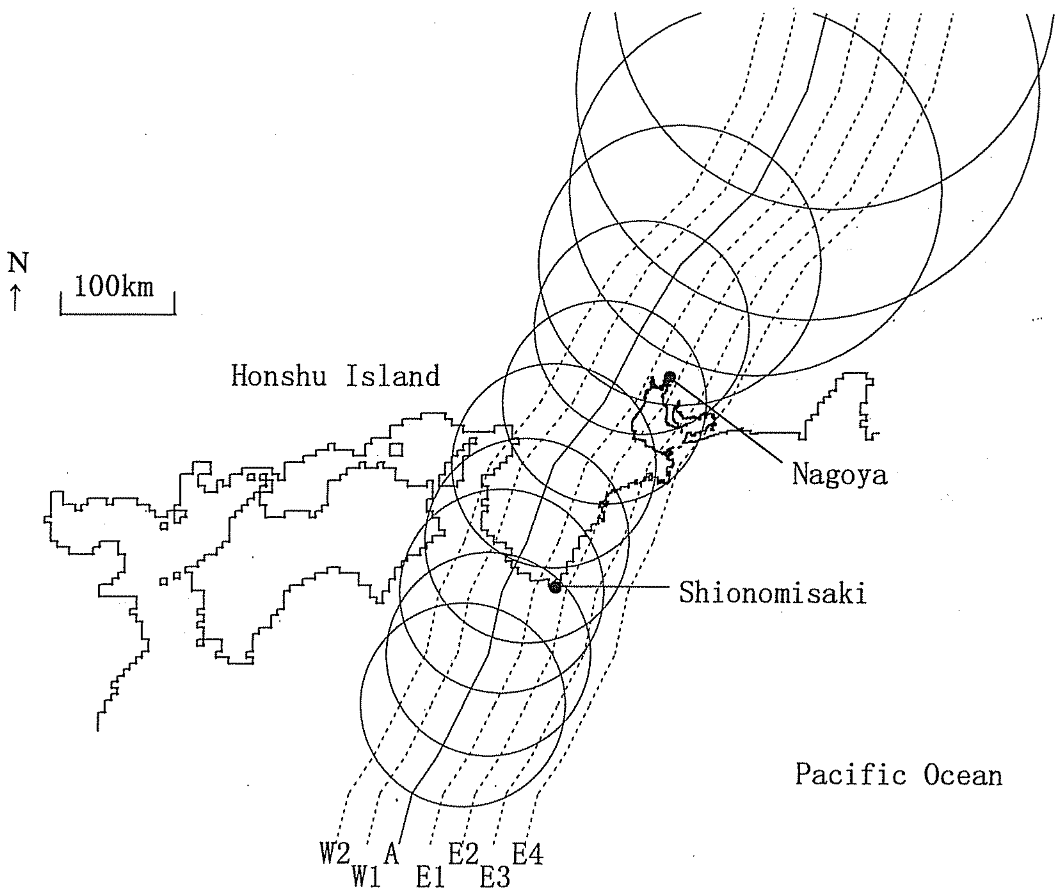


Figure 8 Typhoon routes simulated in this paper

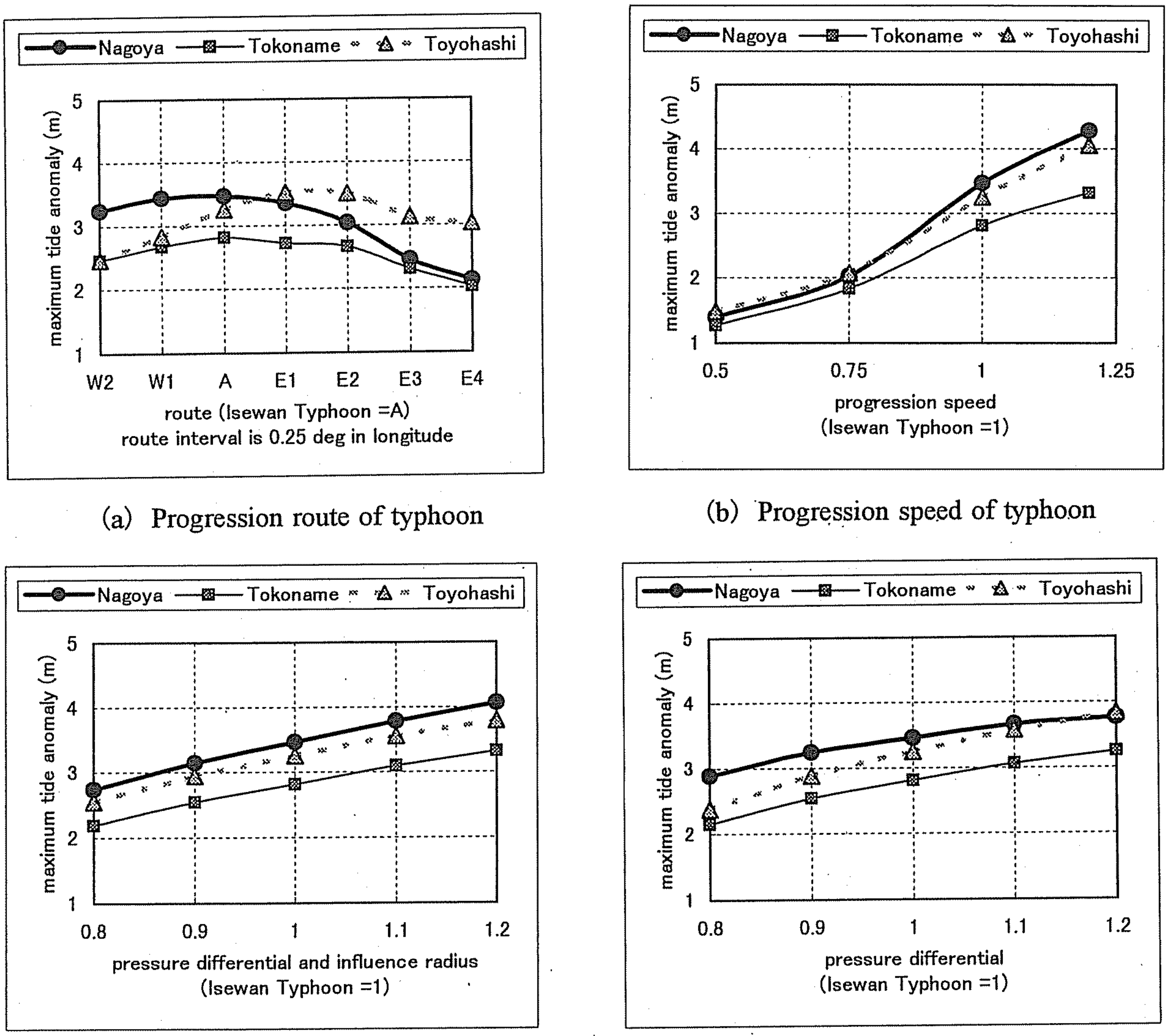
On the other hand, the routes E1 and E2, namely to the east by 0.25 and 0.5 degree from the actual route respectively, become most dangerous at Toyohashi in Mikawa Bay. The route E2 is most similar to the actual route of the typhoon No.13 in 1953, which gave more enormous disaster in Mikawa Bay than the Isewan Typhoon.

Figure 10 shows the most dangerous typhoon route at each place in Ise and Mikawa Bay, and **Figure 11** the largest value of the maximum meteorological tide anomalies for various imaginary typhoon routes.

(3) Progression speed of typhoon

There are two components in winds caused by a typhoon. One is marine winds of which speed was shown in **equation (3)**, and the other is the effect of the movement of a typhoon shown in **equation (4)**.

Figure 9(b) shows the meteorological tide anomalies for various typhoon speeds. The tide anomaly is directly proportional to the progression speed of a typhoon. The Isewan Typhoon



(a) Progression route of typhoon

(b) Progression speed of typhoon

(c) Pressure differential and radius of typhoon

(d) Influence radius of typhoon

Figure 9 Maximum meteorological tide anomalies in various typhoon conditions

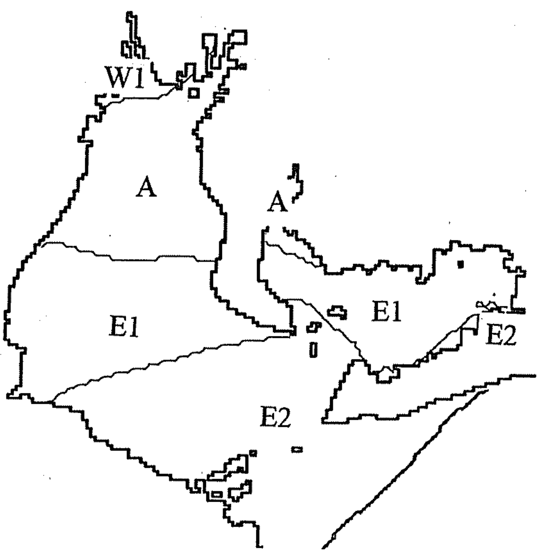


Figure 10 Most dangerous typhoon route at each place in Ise and Mikawa Bay

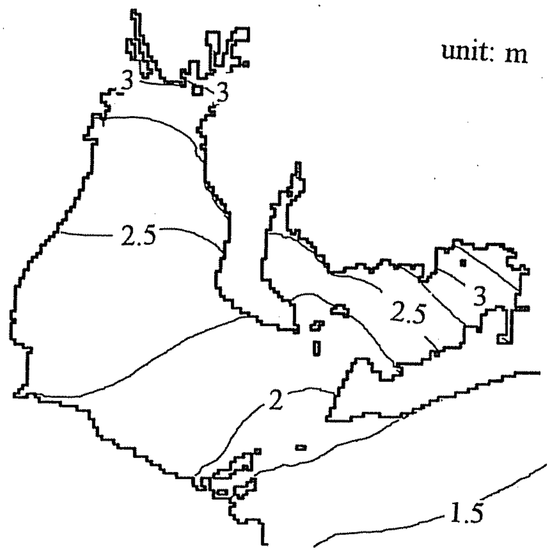


Figure 11 Largest value of maximum meteorological tide anomalies for various typhoon routes

passed the west side of Ise Bay at a speed of 70 km/h. If the speed was half, the peak value of the tide anomaly would become less than half.

(4) Pressure differential and influence radius of typhoon

The speed of marine winds depends on the pressure differential and influence radius of a typhoon. A large meteorological tide anomaly may be caused again in the future by a violent typhoon such as the Isewan Typhoon. It is very difficult to confirm at the present whether the occurrence probability of a violent typhoon increases due to global warming or not. However, it is reported by Nagai (1) that the yearly mean offshore wave height along the Japan Islands in the Pacific Ocean is increasing gradually.

Figure 9 (c) shows the maximum meteorological tide anomalies for the typhoons with various pressure differentials and influence radiuses. If both the pressure differential and the influence radius becomes larger than those of the Isewan Typhoon by 10%, the tide anomaly may increase by 0.2 ~ 0.35 m.

Figure 9 (d) shows the effect of only the pressure differential on the maximum meteorological tide anomaly. Even if only the pressure differential becomes larger than that of the Isewan Typhoon by 10%, the tide anomaly becomes larger by around 0.3 m.

(5) Mean sea level

It is forecasted by numerical models and confirmed by field observations for long years that mean sea level rises gradually due to global warming.

Nakatsuji et al. (2) have reported that the meteorological tide anomaly in Osaka Bay by the Muroto No.2 Typhoon, giving enormous damage there in 1961, may decrease by a few centimeters due to mean water level rising. Isobe et al. (3) also obtained the similar result in Tokyo Bay.

Figure 12 shows the maximum meteorological tide anomalies for various sea levels. The sea level becomes higher by 1 meter, the tide ano-

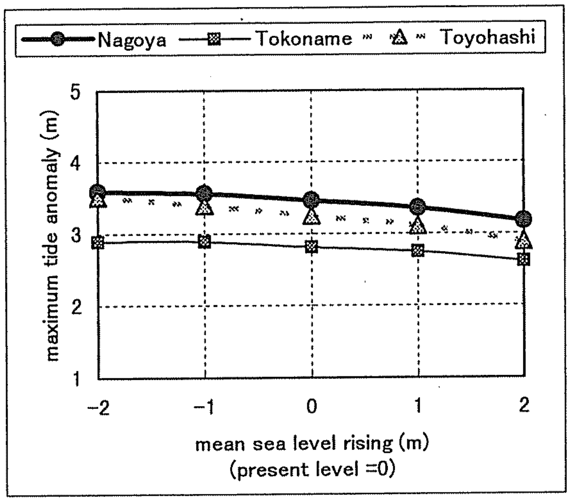


Figure 12 Maximum Meteorological Tide Anomaly for Various Sea Level

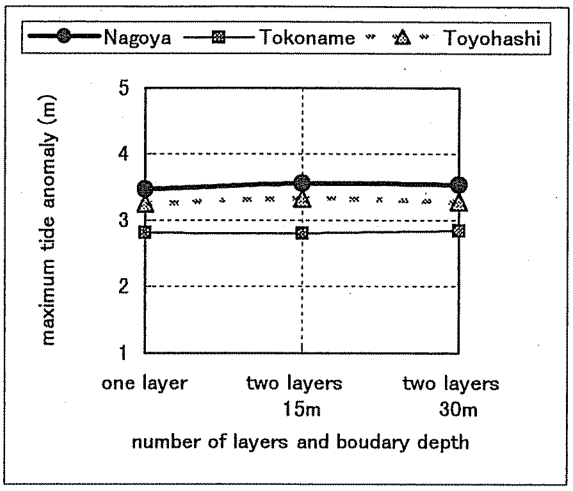


Figure 13 Comparison with the Meteorologicl Tide Anomaly by Two Layer Model

maly becomes smaller by only around 0.1 m. It means that the total tidal level becomes higher by 0.9 m under the mean sea level rising of 1.0 m.

(6) Number of layers in numerical model

The meteorological tide anomaly shown in the **paragraphs (1)** to **(5)** are obtained by one layer model. **Figure 13** shows the comparison with the tide anomaly by two layer model. The water depth at the boundary between the upper layer and the lower is assumed to be 15 and 30 m. The difference of the maximum meteorological tide amonalies among them is quite small, therefore one layer model has enough accuracy for the estimation of the meteorological tide anomaly in Ise and Mikawa Bay.

5. CONCLUSION

The meteorological tide anomaly depends on the route, progression speed, pressure differential, and influence radius of a typhoon. It is confirmed that the route of the Isewan Typhoon was most dangerous for the coast of Ise Bay. On the other hand, the mean sea level rising due to global warming in the future seems to give few effect on the meteorological tide anomaly.

We are in the 40th year after the enormous disaster caused by the Isewan Typhoon. Fortunately we have had no terrible typhoon since then. However it is possible to appear again. The mean sea level rising will reduce the crest heights of port facilities and coastal dikes. Therefore, it is necessary to recall the memory of the disaster, and confirm the safety degree of port facilities, coastal dikes, and residential areas at their backward.

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