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# Chapter

# Long-Wave Generation due to Atmospheric-Pressure Variation and Harbor Oscillation in Harbors of Various Shapes and Countermeasures against Meteotsunamis

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# Abstract

First, the generation and propagation of long ocean waves due to the atmospheric-pressure variation have been simulated using the numerical model based on the nonlinear shallow water equations, where the atmospheric-pressure waves of various pressure-profile patterns travel eastward over East China Sea. Before the oscillation attenuation in Urauchi Bay, Japan, the incidence of long waves can continue owing to an oscillation system generated between the main island of Kyushu and Okinawa Trough. Second, the simple estimate equations are proposed to predict both the wave height and wavelength of long waves caused by an atmospheric-pressure wave, using atmospheric-pressure data above the ocean. Third, numerical simulation has been generated for the oscillation in the harbors of C-, I-, L-, and T-type shapes, as well as Urauchi Bay with two bay heads like a T-type harbor. Finally, we discuss disaster measures, including the real-time prediction of meteotsunami generation, as well as both the structural and the nonstructural preparations.

**Keywords:** meteotsunami, long wave, atmospheric pressure, harbor oscillation, secondary undulation, submarine trough, East China Sea, real-time prediction

# 1. Introduction

At Urauchi Bay of Kamikoshiki Island, situated in the western offing of Kyushu Island, Japan, as shown in **Figure 1**, heavy harbor oscillations occurred during February 24–26, 2009, where the maximum total amplitude of water level reached 3.0 m [1], resulting in that eight fishing boats were capsized and several houses were flooded, as shown in **Figures 2–4**. In terms of time, Japan Standard Time (JST) is used in this chapter. According to the Grid-Point-Value (GPV) pressure data, published by Japan Meteorological Agency (JMA), atmospheric-pressure waves propagated almost eastward over East China Sea, during this term.



Figure 1.

The still water depth around both the main island of Kyushu, and Urauchi Bay in Kamikoshiki Island, Kagoshima Prefecture, Japan. East China Sea is spread to the west of these islands.



Figure 2.

The refloatation operation for the fallen fishing boats around 8:00 (the left-hand side), and eight flooded cars at 8:33 (the right-hand side), on February 25, 2009. These photos were taken by Satsumasendai City Office at Oshima Fishing Port, which is located at one of two heads of Urauchi Bay, as indicated in **Figure 1**.

Such atmospheric-pressure waves propagating over the sea surface have often generated significant long ocean waves, through an amplification mechanism, that is, the Proudman resonance [2], especially when the phase velocity of the atmospheric-pressure wave is close to that of the long ocean waves, as examined by, for example, Hibiya and Kajiura [3] and Vilibic et al. [4], where they numerically reproduced the large harbor oscillation in Nagasaki Bay, Kyushu, Japan, and that in Ciudadella Harbor, Balearic Islands, Spain, respectively. Once long ocean waves are generated by meteorological disturbance due to the instability of a wintry weather system, as well as a storm, and reach a nearshore zone, the wave height of the secondary undulation increases owing to the decrease of water depth, like a tsunami caused by a submarine earthquake (e.g., [5]), a land slide (e.g., [6]), etc., such that



#### Figure 3.

The receding flows through the seawall at 8:36 on February 25, 2009 (the left-hand side), and an inundated house fence (the right-hand side). These photos were taken by Satsumasendai City Office at and near Oshima Fishing Port, respectively.





#### Figure 4.

A damaged fishing boat (the left-hand side), and the basement of a jetty, where part of armor stones have been flowed out (the right-hand side). These photos were taken by the author at Oshima Fishing Port on February 28, 2009.

the long waves are called "meteotsunamis." Meteotsunamis amplified depending on the conditions of atmospheric-pressure waves [7] can become external forces to create huge oscillation, severe inundation, etc. to coastal areas. Long ocean waves supposed to be meteotsunamis have been discussed based on observed data for many coastal zones, considering local characteristics concerning both geographic features and meteorological phenomena (e.g. [8, 9]); Bailey et al. [10] reported meteotsunamis caused by storms, which attacked the east coasts of the United States, facing the continental shelf; recent meteotsunami cases around the world were summarized by Tanaka and Ito [11]. In nearshore zones, meteotsunamis are amplified through not only shoaling but also harbor oscillation in ports, harbors, and bays. Harbor oscillation, also called seiche, with the harbor paradox [12], depends on incident-wave period, harbor shape, and water depth. The oscillation in harbors of various horizontal shapes has been studied using linear theories [13], hydraulic experiments [14], nonlinear numerical models [15], etc.

In this chapter, first, we numerically simulate long ocean waves due to atmospheric-pressure waves with different pressure-profile patterns, including the atmospheric-pressure waves that caused the large harbor oscillation in Urauchi Bay on February 25, 2009. Second, simple estimate equations concerning both the wave height and wavelength of long waves generated by atmospheric-pressure variation are proposed using atmospheric-pressure data above the ocean, for easy prediction methods are required for disaster prevention by, for example, fisheries cooperatives and local authorities, although the numerical computation is necessary to research both the mechanisms and characteristics of meteotsunamis. Third, we apply a numerical model based on the nonlinear shallow water equations, to study oscillation in harbors of various shapes, including the types of "L," "I" with a narrow region, "I" with a seabed crest or trough, "C," and "T," as well as Urauchi Bay, which has two heads like a T-type harbor. Finally, we discuss disaster measures against meteotsunamis, generated to propagate toward the west coasts of Kyushu. Several methods for the real-time prediction of meteotsunami generation are proposed, using an inverse analysis, as well as the proposed simple prediction equations, after which both the structural and the nonstructural preparations for meteotsunamis are summarized.

# 2. Numerical model and calculation conditions

A set of nonlinear shallow water equations, in consideration of atmosphericpressure gradient at the sea surface, is solved in the horizontal two dimensions by applying a finite difference method. The fundamental equations are

$$\frac{\partial \eta}{\partial t} + \frac{\partial}{\partial x} \{(\eta + h)U\} + \frac{\partial}{\partial y} \{(\eta + h)V\} = 0, \qquad (1)$$

$$\frac{\partial U}{\partial t} + \frac{\partial U^2}{\partial x} + \frac{\partial (UV)}{\partial y} = fV - g\frac{\partial \eta}{\partial x} - \frac{1}{\rho}\frac{\partial P}{\partial x} + A_h \left(\frac{\partial^2 U}{\partial x^2} + \frac{\partial^2 U}{\partial y^2}\right) - \frac{KU\sqrt{U^2 + V^2}}{\eta + h}, \qquad (2)$$

$$\frac{\partial V}{\partial t} + \frac{\partial (UV)}{\partial x} + \frac{\partial V^2}{\partial y} = -fU - g\frac{\partial \eta}{\partial y} - \frac{1}{\rho}\frac{\partial P}{\partial y} + A_h \left(\frac{\partial^2 V}{\partial x^2} + \frac{\partial^2 V}{\partial y^2}\right) - \frac{KV\sqrt{U^2 + V^2}}{\eta + h}, \qquad (3)$$

where *U* and *V* are horizontal velocities in the *x* and *y* directions, respectively;  $\eta$ , *h*, and *P* are water surface displacement, still water depth, and atmospheric pressure at the water surface, respectively; *f* and *A<sub>h</sub>* are the Coriolis coefficient and horizontal eddy viscosity coefficient, respectively. In the present study, gravitational acceleration  $g = 9.8 \text{ m/s}^2$ , seabed friction coefficient  $K = 2.6 \times 10^{-3}$ , and seawater density  $\rho = 1035.0 \text{ kg/m}^3$ . The Sommerfeld radiation condition is adopted at the boundaries of the computational domain, while the boundaries between land and sea are assumed to be vertical walls with the perfect reflection of waves.

#### 3. Long-wave generation due to atmospheric-pressure waves

# 3.1 The relationship between the parameters of atmospheric-pressure waves and long-wave generation

In the large area along the west coasts of Kyushu, as well as Yamaguchi Prefecture nearby Kyushu, secondary undulation, supposed to be caused by atmospheric-pressure disturbance above East China Sea, often increases from February to April, sometimes leading to disasters as mentioned above. In this section, we discuss the relationship between the parameters of atmospheric-pressure waves and long-wave generation in the ocean. The computational domain is part of East China Sea, where the longitude is from 123.0 to 131.0°E, and the latitude is from 30.0 to 32.5°N, with the actual seabed configuration. The still water depth in East China Sea near the main island of Kyushu is shown in **Figure 5**, where it is around 800 m at the deepest site in Okinawa Trough. The grid widths  $\Delta x$  and  $\Delta y$  are 790.0 and 925.0 m, respectively, while the time step  $\Delta t$  is 2.0 s. In this section, the Coriolis coefficient f and horizontal eddy viscosity coefficient  $A_h$  in Eqs. (2) and (3) are 7.3 × 10<sup>-5</sup> s<sup>-1</sup> and 100.0 m<sup>2</sup>/s, respectively.

In the computation, it is assumed that the atmospheric pressure is uniform from north to south, and atmospheric-pressure waves travel eastward at a constant phase velocity over East China Sea. The distribution of atmospheric pressure along the latitude lines is classified into four patterns shown in **Figure 6**, based on the GPV



#### Figure 5.

The still water depth in East China Sea near the main island of Kyushu. The point indicated with ① is located off the mouth of Urauchi Bay, where the huge harbor oscillation of 3.0 m in total amplitude was observed. The still water depth is around 800 m at the deepest site in Okinawa Trough.



#### Figure 6.

Typical four patterns for the high-pressure profiles of atmospheric-pressure waves, propagating rightward.  $P_{max}$  is the maximum value of pressure, while  $P_o$  is a stable value of pressure, where  $P_o = 0$  in (a),  $P_o = P_{max}$  in (b), and  $P_o < P_{max}$  in (c) and (d).

pressure data, where the atmospheric pressure P is a deviation from the value of pressure for an average atmospheric-pressure condition. It should be noted that an atmospheric-pressure wave is not a pressure wave in fluids, including a sound wave and a shock wave, but the propagation of an atmospheric-pressure profile.

An atmospheric-pressure wave of pattern (a), for example, has three parameters, that is, wavelength L, the maximum value of pressure,  $P_{\text{max}}$ , and phase velocity  $C_p$ , where these values are kept constant before the wave stops in the numerical calculation. The pressure profile for an atmospheric-pressure wave of pattern (a) is described as

$$P(x,t_0) = \begin{cases} \frac{p_{\max}}{2} \left\{ 1 + \cos\left[\frac{2\pi}{L}(x-x_c)\right] \right\} & (|x-x_c| \le L/2), \\ 0 & (|x-x_c| > L/2), \end{cases}$$
(4)

where the initial position of the pressure peak,  $x_c$ , is at the longitude of 124°E.



The water surface displacements at Point <sup>(1)</sup> indicated in **Figure 5**, for various values of P<sub>max</sub>. The wave profile of atmospheric pressure is pattern (a), where L = 10.0 km,  $C_p$  = 20.0 m/s, and  $P_{max}$  = 1.0, 2.0, or 3.0 hPa. The still water depth is about 22.0 m at Point <sup>①</sup>.

Figure 7 shows the numerical calculation results of water surface displacements at Point 1 indicated in Figure 5, owing to an assumed atmospheric-pressure wave of pattern (a), where L = 10.0 km,  $C_p = 20.0$  m/s, and  $P_{max} = 1.0$ , 2.0, or 3.0 hPa. Point ① is located off the mouth of Urauchi Bay, where the huge harbor oscillation of 3.0 m in total amplitude was observed, as mentioned above. The wave height of the generated long waves at Point ① is almost in proportion to  $P_{\text{max}}$ , which has been also confirmed at the other monitoring points near Danjyo Islands or Uji Islands. According to **Figure 7**, many long waves propagate through Point ①, owing to the travel of one atmospheric-pressure wave.

Shown in Figure 8 is the wave height and period of the long wave with the maximum wave height at Point ① indicated in **Figure 5**, for various values of  $C_p$ , where the wave profile of atmospheric pressure is pattern (a); L = 30.0 km and  $P_{\text{max}}$  = 1.0 hPa; the waves are defined using the zero-up-cross method. Inside the area from 125.5 to 127.0°E, and from 30.0 to 32.5°N, the average value of still water depth is 80 m, or 100 m, over the continental shelf, such that the Proudman resonance for long ocean waves can occur when the phase velocity of an atmospheric-pressure wave,  $C_p$ , is around the phase velocity of linear shallow water waves, that is,  $\sqrt{gh} \approx 30$  m/s. According to **Figure 8**, the wave height of the long ocean waves increases as  $C_p$  is close to 32.0 m/s.



Figure 8.

The wave height and period of the long wave with the maximum wave height at point 10 indicated in Figure 5, for various values of  $C_p$ . The wave profile of atmospheric pressure is pattern (a), where L = 30.0 km and  $P_{max} = 1.0 \ hPa.$ 

# 3.2 The long waves on the days when large harbor oscillation occurred in Urauchi Bay

The pressure profiles for atmospheric-pressure waves of patterns (b), (c), and (d) shown in **Figure 6** are described for  $|x - x_c| \le L/2$  as

(b): 
$$P(x,t_0) = P_0\{1 - \sin[\pi(x-x_c)/L]\}/2,$$
 (5)

respectively, while  $P(x, t_0) = P_0(x < x_c - L/2)$  and  $P(x, t_0) = 0.0$  ( $x > x_c + L/2$ ). In Eq. (7),  $x_d$  is the initial position of the second pressure peak, and the power  $\kappa$  is 0.02x.

The parameters of each pattern are evaluated based on the GPV pressure data on the days when large harbor oscillation occurred in Urauchi Bay. For example, the time variation of GPV pressure distribution on February 25, 2009, when the largest harbor oscillation was observed in Urauchi Bay from 2009 to 2018, is shown in **Figure 9**.

**Figure 10** shows the pressure profiles along three latitudes of 30.0, 30.5, and 31.0°N, at 3:00 on February 25, 2009, according to the GPV pressure data shown in **Figure 9**. An atmospheric-pressure wave, where the pressure gap was 4–5 hPa, and the total wavelength was 80–120 km, traveled almost eastward over East China Sea, at the phase velocity of around 140 km/h from 3:00 to 4:00, 120 km/h from 4:00 to 5:00, and 150 km/h from 5:00 to 6:00, such that the wave profile of the atmospheric pressure on the day is described with pattern (d), where the mean values of the parameters, that is, *L*, *P*<sub>max</sub>, and *C*<sub>p</sub>, are 90.0 km, 4.0 hPa, and 38.6 m/s, respectively.



#### Figure 9.

The time variation of the GPV pressure distribution on February 25, 2009, when the huge harbor oscillation of 3.0 m in total amplitude was observed in Urauchi Bay. The GPV pressure data were published by Japan Meteorological Agency.



#### Figure 10.

The GPV pressure distributions along three latitudes of 30.0, 30.5, and 31.0°N, at 3:00 on February 25, 2009. The solid, dotted, and chain double-dashed lines show the pressure along the latitudes of 30.0, 30.5, and 31.0° N, respectively.



Figure 11.

The numerical result for the time variation of water level distribution on February 25, 2009. The wave profile of atmospheric pressure is pattern (d), where L = 90.0 km,  $P_{max} = 4.0 \text{ hPa}$ , and  $C_p = 38.6 \text{ m/s}$ .

Depicted in **Figure 11** is the numerical result for the time variation of water level distribution due to the atmospheric-pressure waves, where the pressure profile is pattern (d), and its parameters L,  $P_{max}$ , and  $C_p$  are 90.0 km, 4.0 hPa, and 38.6 m/s, respectively. The waves show refraction over Okinawa Trough, for the phase velocity of the generated long waves decreases over the deep trough, after which they propagate to the northeast, as pointed out by Katayama et al. [16].

The numerical result for the water surface displacement at Point ① indicated in **Figure 5** is shown in **Figure 12**, where the wave height of the first three waves is over 1 m, and the wave period of the first to the fifth waves is about 1000, 750, 700, 760, and 660 s, respectively.

According to the observed data [9], large harbor oscillation also occurred in Urauchi Bay on March 3, 5, and 6, 2010, where the wave profiles of atmospheric pressure are described by patterns (b), (c), and (d), respectively, based on the corresponding GPV pressure data, and the mean values of the parameters (L,  $P_{max}$ , and  $C_p$ ) are (100.0 km, 3.0 hPa, 20.0 m/s), (100.0 km, 4.0 hPa, 33.0 m/s), and (90.0 km, 4.0 hPa, 25.0 m/s), respectively. Shown in **Figure 13** are the numerical calculation results for the water surface displacements at Point ① indicated in **Figure 5**, originating from the atmospheric-pressure waves of patterns (b), (c), and (d),



Figure 12.

The numerical result for the water surface displacement at point ① indicated in **Figure 5**, on February 25, 2009. The wave profile of atmospheric pressure is pattern (d), where L = 90.0 km,  $P_{max} = 4.0$  hPa, and  $C_p = 38.6$  m/s.



#### Figure 13.

The numerical results for the water surface displacements at Point ① indicated in **Figure 5**. The wave profiles of atmospheric pressure are patterns (b), (c), and (d), where the parameters (L, P<sub>max</sub>, and C<sub>p</sub>) are (100.0 km, 3.0 hPa, 20.0 m/s), (100.0 km, 4.0 hPa, 33.0 m/s), and (90.0 km, 4.0 hPa, 25.0 m/s), respectively.

with the abovementioned mean values of their parameters. The wave height of the long waves due to the atmospheric-pressure wave of pattern (b) is lower than that in the other cases, for the atmospheric pressure does not decrease after its increase. If the sea surface, which has been pressed down, is relieved owing to attenuation in atmospheric pressure, the balance between the atmospheric pressure and the water surface gradient is not maintained, resulting in the production and propagation of free-surface waves, and the Proudman resonance appears when the moving velocity of the recovery point of atmospheric pressure matches the phase velocity of long ocean waves. Although the reason why the harbor oscillation in Urauchi Bay was rather large on March 3, 2010, is thought to be linked to the instability in atmospheric pressure before the day, future work is required.

Conversely, the long waves generated by the atmospheric-pressure wave of pattern (d) show remarkable wave height of 1.1 m, where the atmospheric pressure decreases after its increase. The wave period of the first wave is about 1300 s, while that of the second and the third waves is about 1250 and 900 s, respectively. These values of wave period, as well as the numbers of exited long waves, concern the amplification of harbor oscillation, as discussed in the following sections. The long waves due to the atmospheric-pressure wave of pattern (c) also show the maximum

wave height of about 0.3 m, and the wave period of the long wave with the maximum wave height is around 2600 s.

# 4. Oscillation system between the main island of Kyushu and Okinawa Trough

The amplification of harbor oscillation requires continuous wave energy incidence into the harbor. **Figure 14** shows the water surface displacements at Point ①, off the mouth of Urauchi Bay, owing to the atmospheric-pressure wave of pattern (a), where L = 10.0 km,  $P_{\text{max}} = 1.0$  hPa, and  $C_p = 20.0$  m/s. In the figure, the numerical result, in consideration of wave reflection at the west coasts of the main island of Kyushu, is compared with that without wave reflection at the west coasts of the main island of Kyushu, where the target domain for the latter is a restricted area between 123°E and 130°E. In the former case, an oscillation system is generated off the southern Kyushu, between the main island of Kyushu and Okinawa Trough, resulting in the continuous motion of water surface, to make heavier harbor oscillation in, for example, Urauchi Bay. Another oscillation system off the northern Kyushu may also appear between the main island of Kyushu and other islands, without the submarine trough, as suggested by Hibiya and Kajiura [3].

In order to examine the generation of an oscillation system between Okinawa Trough and the main island of Kyushu, we perform numerical experiments for a hypothetical seabed configuration. **Figure 15(a)** shows the actual seabed configuration along the latitude of 31.8°E, where Urauchi Bay is located as shown in **Figure 5**, while **Figure 15(b)** shows the hypothetical seabed configuration, where the trough length is extended to make the distance between wave reflection points larger. In both cases, the perfect reflection boundary condition is adopted at the west coasts of the main island of Kyushu.

In the one-dimensional computation for long waves, the nonlinear surface wave equations based on a variational principle [17] is applied to consider both the strong nonlinearity and dispersion of long waves over the shallower areas, as well as the deeper trough, where the velocity potential is assumed to show a linear distribution in the vertical direction. The water surface profile is given by  $\eta$  (m) = -0.2 m sin  $[2\pi(x - 790.0 \text{ km})/27.7 \text{ km}]$  (790.0 km  $\leq x \leq 817.7 \text{ km}$ ), and the velocity potential is zero everywhere, at the initial time. **Figure 16** shows the water surface displacements at Points P1–P5, for the hypothetical seabed configuration illustrated in **Figure 15(b)**, where the fundamental equations were solved using the implicit



#### Figure 14.

The numerical results for the water surface displacements at point ① indicated in **Figure 5**. The atmosphericpressure profile is pattern (a), where L = 10.0 km,  $P_{max} = 1.0$  hPa, and  $C_p = 20.0$  m/s. The solid and broken lines represent the results with and without wave reflection at the west coasts of the main island of Kyushu, respectively.



Figure 15.

The seabed configurations of East China Sea along the latitude of 31.8°E: The actual seabed configuration (a), and a hypothetical seabed configuration with an extended trough (b).



Figure 16.

The water surface displacements at the Points  $P_{1}-P_{5}$  for the hypothetical seabed configuration illustrated in *Figure 15(b)*.

scheme [18]. An oscillation system with repeated reciprocation of long waves has been built up, resulting in the periodical oscillation at Point P4, where Koshiki Islands are situated. Such continuous undulation in water surface contributes to amplify harbor oscillation in bays and harbors at the west coasts of the southern Kyushu.

# 5. Simple method to estimate long waves due to an atmosphericpressure wave

# 5.1 Estimate equations for the wave height and wavelength of generated long waves

As mentioned in Section 1, long waves due to atmospheric-pressure variation can cause large harbor oscillation, resulting in hazards including the damages of fish boats and the inundation of houses, such that it is necessary for fishing cooperatives, town offices, etc. to prevent such hazards. If a simple method to predict the generation of serious long ocean waves is available, then they can make provision against meteotsunamis, several hours before. In this section, we propose equations to estimate both the wave height and wavelength of coming long ocean waves, using the measured or GPV data of atmospheric pressure, without derivation, integration, or complex numerical calculation.

It is assumed that the distribution of atmospheric pressure p above the outer sea is trapezoidal at the initial time t = 0.0 s, as shown in **Figure 17**, where the profile for a low-pressure case is illustrated, after which the atmospheric-pressure wave propagates stably at a constant phase velocity, in the positive direction of the *x*-axis.

The water surface is assumed to rise 1.0 cm owing to the pressure decrease of 1.0 hPa, and then the initial profile of water surface is also trapezoidal as shown in **Figure 18**. The maximum value of water surface displacement is -P/10,000 (m) for  $x_0 + D_P \le x \le x_0 + D_P + L_P$  at  $t = t_0$ , where P (Pa) < 0 is the minimum pressure value of the atmospheric-pressure wave shown in **Figure 17**, and  $L_P$  is the distance where its pressure value hardly shows variation.

After the initial condition shown in **Figure 17**, side AB of the low-pressure profile moves at a constant phase velocity, resulting in a gradual recovery of atmospheric pressure from the low-pressure condition. The moving velocity of point A, where the pressure recovery starts, that is, the phase velocity of the atmosphericpressure wave,  $C_P$ , is assumed to equal the phase velocity of long ocean waves, C, to



Figure 17.

The initial atmospheric-pressure distribution of a low-pressure wave. After the initial time, the pressure wave propagates at a constant phase velocity in the positive direction of the x-axis.



Figure 18. The initial water surface profile due to the initial atmospheric-pressure distribution shown in Figure 17.

consider a sever case due to the Proudman resonance. It is also assumed that the wavelength of long ocean waves,  $\lambda$ , is much larger than the still water depth h, that is,  $h/\lambda \ll 1$ , such that  $C_P = C = \sqrt{gh}$ .

When  $t = \Delta t$ , the positions of points A and B become  $x = x_0 + \Delta L$  and  $x = x_0 + D_P + \Delta L$ , respectively, where  $\Delta L = C_P \Delta t$ . The water body CDFE sketched in **Figure 19**, which is part of the raised water at the initial time, is relieved owing to the recovery of the low pressure during  $\Delta t$ .

The parallelogram CDFE, which we call  $S_0$ , shown in **Figure 19**, corresponds to the trapezoid  $S_1$  shown in **Figure 20**, where the height and the length of lower base of the trapezoid  $S_1$  are a (m) =  $-P\Delta L/D_P/10,000$  and  $L_1 = D_P + \Delta L$ , respectively, for side EF shown in **Figure 19** is an isopotential energy level at  $t = \Delta t$ . The relieved water body  $S_1$  transforms to two long ocean waves, propagating in the positive and negative directions of the *x*-axis, where the wave height, the wavelength, and the absolute value of phase velocity, of the two long waves, are approximately a/2,  $L_1$ , and C, respectively.

Through the recovery of low pressure after  $t = \Delta t$ , the relief of water body is repeated, such that the long ocean wave, propagating in the positive direction of the *x*-axis, is overlapped by other long waves generated continuously. Consequently, the wave amplitude *H* and wavelength  $\lambda$  of the long wave traveling in the positive direction of the *x*-axis are estimated by

$$H = (-PL_P/D_P)/20,000 \text{ (m)}, \tag{8}$$

$$\lambda = D_P, \tag{9}$$



Figure 19.

An enlarged illustration of part of the water surface profile shown in **Figure 18**. Side AB of the low-pressure profile shown in **Figure 17**, is above side DC of the water surface profile at t = 0.0 s, after which side AB comes above side FE at  $t = \Delta t$ .



#### Figure 20.

An aggregation of water columns,  $S_0$ , relieved owing to the recovery of low pressure (a), and the corresponding trapezoidal water body  $S_1$  (b).

respectively. When  $L_P$  is the moving distance of side AB, Eq. (8) corresponds to the prediction equation shown by Hibiya and Kajiura [3], using the method of characteristics. The parameters P,  $L_P$ , and  $D_P$  can be evaluated according to the observed or GPV pressure data for the wave profile of an atmospheric-pressure wave.

Conversely, if we observe the time variation of atmospheric pressure at several offshore sites, to obtain the recovery rate of pressure p, that is,  $r_P$ , which is defined by  $\partial p/\partial t$ , the estimate equation for H is

 $H = (r_P L_P / C_P) / 20,000 (m),$ 

(10)

for  $r_P$  corresponds to  $-PC_P/D_P$  (Pa/s), according to **Figure 17**. It is noted that Eqs. (8)–(10) can be also applied to high-pressure cases, where the positive value *P* is the highest value of atmospheric pressure.

#### 5.2 The validation of predicted values through the estimate equations

Several results through the proposed estimate equations, that is, Eqs. (8) and (9), are compared with the corresponding numerical results obtained using the numerical model based on Eqs. (1)–(3), for the one-dimensional generation and propagation of meteotsunamis. The still water depth h is assumed to be uniformly 100.0 m. In the numerical computation, the distribution of atmospheric pressure at the water surface is changed gradually from zero to a low-pressure distribution as shown in **Figure 17**, resulting in a water surface profile as shown in **Figure 18**. After obtaining the initial steady state, side AB shown in **Figure 17** moves at  $C_P = C = \sqrt{gh}$ . The Coriolis coefficient, seabed friction coefficient, and horizontal eddy viscosity coefficient are zero in Eqs. (1)–(3) for simplicity.

**Figure 21** shows the numerical calculation results of water surface displacements at  $x = x_1$  indicated in **Figure 18**, where P = -400 Pa and  $L_P = 100,000$  m;  $D_P = 12,500, 25,000$ , and 50,000 m. The decrease in water surface displacement  $\eta$ for t < 7,000 s is due to the decrease in atmospheric pressure before the initial time, while the increase in  $\eta$  for t > 11,000 s is caused by the propagation of the



#### Figure 21.

The numerical results of water surface displacements at  $x = x_1$  indicated in **Figure 18**, obtained using the nonlinear shallow water model, for various values of  $D_P$ , where P = -400 Pa;  $L_P = 100,000$  m;  $D_P = 12,500$ , 25,000, and 50,000 m.

Values of pressure parameters				Numerical results obtained using Eqs. (1)–(3)			Estimated values from Eqs. (8) and (9)	
$D_P(\mathbf{m})$	$r_P$ (Pa/s)	$L_P(\mathbf{m})$	P (Pa)	<i>H</i> (m)	λ (m)	T (s)	<i>H</i> (m)	λ (m)
12,500	1.00	50,000	-400	0.080	12,500	400	0.08	12,500
		100,000	-200	0.080	_		0.08	_
			-400	0.160	_		0.16	_
	-1.00	100,000	400	-0.160			-0.16	_
25,000	0.50	50,000	-400	0.040	25,000	800	0.04	25,000
		100,000	-200	0.040			0.04	
			-400	0.080			0.08	7
	-0.50	100,000	400	-0.080			-0.08	
50,000	0.25	50,000	-400	0.020	50,000	1600	0.02	50,000
		100,000	-200	0.020			0.02	_
			-400	0.040	_		0.04	_
	-0.25	100,000	400	-0.040	_		-0.04	_

#### Table 1.

The wave amplitude H, wavelength  $\lambda$ , and wave period T of the generated long ocean waves, at  $x = x_1$  indicated in **Figure 18**, obtained using the numerical model based on the nonlinear shallow water equations, that is, Eqs. (1)–(3), as well as the estimated values of H and  $\lambda$  through Eqs. (8) and (9), where  $D_P$ ,  $L_P$ , and P are defined in **Figure 17**;  $r_P$  is the recovery rate of atmospheric pressure.

atmospheric-pressure waves. As  $D_P$  is decreased, the wavelength of the meteotsunamis decreases, but their wave height increases.

Shown in **Table 1** are the numerical results of wave amplitude H, wavelength  $\lambda$ , and wave period T, for the generated long waves propagating through  $x = x_1$  indicated in **Figure 18**, in comparison with the corresponding estimated values of both H and  $\lambda$  from Eqs. (8) and (9), respectively. The estimated values show good agreement with the corresponding computational data, such that the proposed estimate equations are available to predict the approximate values of both the wave height and wavelength of severe meteotsunamis, using observed or GPV atmospheric-pressure data.

# 6. Numerical calculation for harbor oscillation in harbors of various shapes

### 6.1 Numerical calculation conditions

Meteotsunamis can be amplified to be heavier through harbor oscillation, as well as shoaling. In this chapter, we discuss oscillation in harbors of various shapes, by applying the numerical model based on the nonlinear shallow water equations, that is, Eqs. (1)–(3). The Coriolis coefficient f and horizontal eddy viscosity coefficient  $A_h$  are 0.0 s<sup>-1</sup> and 30.0 m<sup>2</sup>/s, respectively. Illustrated in **Figure 22** is an example of computational domains, where the harbor of a horizontally rectangular shape, we call, an I-type harbor. A train of incident regular waves, the wave height of which is 0.2 m, enters the computational domain through its leftward boundary and then propagates inside the harbor, leading to harbor oscillation.

The target harbors are model harbors of various shapes, as well as an actual bay, where the horizontal shapes of the model harbors are I-type, L-type, C-type, and



The computational domain for harbor oscillation in an I-type harbor. The incident waves, the wave height of which is 0.2 m, enter the computational domain through its leftward boundary.

T-type, while the actual bay is Urauchi Bay. We examine numerical calculation results for the amplification factor of wave height due to oscillation in these harbors.

# 6.2 Amplification in the L-type harbors

**Figure 23** shows L-type harbors, as well as an I-type harbor, where the harboraxis length is 2000 m, while the bending position of the L-type harbors is different. The still water depth h is 20.0 m in the computational domains.



The horizontal shapes of the L-type harbors with different bending positions, as well as the I-type harbor, where the harbor-axis length is 2000 m. The still water depth h is 2000 m.



Figure 24.

The values of amplification factor R at the head of the L-type harbors with different bending positions LA, as well as that of the I-type harbor with the same harbor-axis length, shown in **Figure 23**.

Shown in **Figure 24** is the amplification factor *R* at the head of the L-type harbors with different bending positions, as well as the I-type harbor, shown in **Figure 23**, where *R* is defined by the ratio between the maximum wave height at each point, and the wave height of the incident waves, that is, 0.2 m; *kl* is dimensionless wave number, that is,  $2\pi l/(T\sqrt{gh})$ . Although both the values of *R* and *kl* for the first mode in all the harbors are almost the same, the value of *R* for the second mode increases as the distance between the bending position and the harbor head, *LA*, is increased. It should be noted that when *LA* is 1000 and 1200 m, the value of *R* at the head of the L-type harbors is larger than that of the I-type harbor with the same harbor-axis length.

## 6.3 Amplification in the I-type harbors with a narrowed area

Figure 25 shows I-type harbors with a narrowed area, where the position, or the width, of the narrowed area is different. The still water depth h is 20.0 m in the computational domains.

Shown in **Figure 26** is the amplification factor *R* at the points indicated in **Figure 25** for the I-type harbors with a narrowed area, where the same symbols are used for the numerical results as that for the corresponding positions shown in **Figure 25**. The value of *R* at the head for the first mode is larger in harbor  $I_2$  than that in harbor  $I_1$ , where the narrowed area is located at the harbor mouth, while the second mode shows the opposite phenomenon. The value of *R* at the head for the



Figure 25.

The horizontal shapes of the I-type harbors with a narrowed area, where the position, or the width, of the narrowed area is different. The harbor length is 2000 m, and the still water depth h is 20.0 m.



#### Figure 26.

The values of amplification factor R at the points indicated in **Figure 25** for the I-type harbors with a narrowed area. The numerical results are represented with the same symbols as that used for the corresponding positions shown in **Figure 25**.



#### Figure 27.

The horizontal shape of the C-type harbor, where two I-type harbors are connected with a rectangular-section channel. The still water depth h is 20.0 m.

second mode is larger in harbor  $I_3$  than that in harbor  $I_4$ , where the harbor width at the narrowed area is narrower than that in harbor  $I_3$ .

#### 6.4 Amplification in the C-type harbor

Depicted in **Figure 27** is a C-type harbor, where two I-type harbors are connected with a rectangular-section channel, such that the C-type harbor has two mouths. The still water depth h is 20.0 m in the computational domain.

**Figure 28** shows the amplification factor *R* in the C-type harbor shown in **Figure 27**. At the heads of the I-type harbors, the long waves coming through two mouths are in almost opposite phase, such that the value of *R* becomes lower than that at the head of the corresponding I-type harbor alone, as shown in **Figure 24**.



#### Figure 28.

The values of amplification factor R at the longitudinal centers of the I-type harbors, the heads of the I-type harbors, and the longitudinal center of the connecting channel, for the C-type harbor shown in **Figure 27**.

Conversely, the amplification factor R for the C-type harbor shows large values at the longitudinal centers of the I-type harbors, as well as that of the connecting channel, for the value of R depends on the phase difference between the long waves coming through two mouths.

#### 6.5 Amplification in the I-type harbors with a seabed crest or trough

Shown in **Figure 29** are the seabed configurations of I-type harbors with a seabed crest or a seabed trough, where the still water depth is 10.5 or 29.5 m at the longitudinal center, respectively; except at the longitudinal center, the seabed is uniformly sloping inside the harbors. The still water depth is 20.0 m at both the head and mouth of the harbors, as well as outside the harbors in the computational domains. The length and width of the harbors are 2000 and 400 m, respectively.

**Figure 30** shows the amplification factor *R* at the head of the I-type harbors with a seabed crest or trough, shown in **Figure 29**, as well as that of the I-type harbor with a flat seabed, shown in **Figure 23**. In the I-type harbor with the seabed crest, the first and the second modes appear at lower values of *kl* than those with the seabed trough, respectively, for the average water depth is shallower in the former than in the latter. At the head of the I-type harbor with the seabed crest, the value of *R* for the first mode is larger than that for the second mode, while at the head of the I-type harbor with the seabed trough, the reverse is true.



Figure 29.

The side views of the I-type harbors with a seabed crest (the left-hand side) and a seabed trough (the right-hand side). The length and width of the harbors are 2000 and 400 m, respectively. The still water depth is 20.0 m outside the harbors in the computational domains.



Figure 30.

The values of amplification factor R at the head of the I-type harbors with the seabed crest or trough shown in **Figure 29**, as well as that with a flat seabed, shown in **Figure 24**.



#### Figure 31.

The horizontal shapes of the T-type harbor (the left-hand side), the I-type harbor (the middle), and the L-type harbor (the right-hand side), where the T-type harbor includes both the I-type and L-type harbors. The harbor width is 600 m, and the still water depth h is 20.0 m.

#### 6.6 Amplification in the T-type harbors

A T-type harbor has two heads, as shown in **Figure 31**, where an I-type and L-type harbors are also depicted for comparison. The harbor width is 600 m, and the still water depth h is 20.0 m in the computational domains.

**Figure 32** shows the amplification factor  $R_m$  at the heads of the T-, I-, and L-type harbors shown in **Figure 31**, where  $R_m$  is defined by the ratio between the maximum wave height at each point and that at the harbor mouth. The second mode, specific to T-type harbors, appears when the wave period of the incident waves, T, is about 640 s, where the oscillation shows antinodes at two heads of the T-type harbor.

#### 6.7 Harbor oscillation in Urauchi Bay

## 6.7.1 Amplification in Urauchi Bay

Urauchi Bay has two bay heads, as shown in **Figure 1**, such that the bay has a shape similar to that of a T-type harbor. **Figure 33** shows the amplification factor  $R_{\rm m}$  at two fishing ports, that is, Oshima Fishing Port and Kuwanoura Fishing Port,



#### Figure 32.

The values of amplification factor  $R_m$  at points A and B, which are located at the heads of the T-, I-, and L-type harbors shown in **Figure 31**, where  $R_m$  is defined by the ratio between the maximum wave height at each point and that at the harbor mouth.



#### Figure 33.

The values of amplification factor  $R_m$  at Oshima and Kuwanoura Fishing Ports facing Urauchi Bay, as shown in **Figure 1**, where the former is located at a bay head, while the latter in another branch is not at another bay head.

facing Urauchi Bay, where the amplification factor  $R_m$  is defined by the ratio between the maximum wave height at each point and that at the bay mouth. It should be noted that Oshima Fishing Port is located at one of the bay heads, while Kuwanoura Fishing Port is at another bay branch, but not at its head. Although the oscillation period T for the first mode is 1580 s at both Oshima and Kuwanoura Fishing Ports, the period T for the second mode is 720 s at Oshima Fishing Port, while 600 s at Kuwanoura Fishing Port. The values of  $R_m$  for both the first and second modes at Oshima Fishing Port, where eight fishing boats capsized owing to the heavy harbor oscillation during February 24–26, 2009, as mentioned above, are larger than those at Kuwanoura Fishing Port, respectively.

#### 6.7.2 Water surface displacements at the ports of Urauchi Bay

The time variations of the water surface displacements at Oshima and Kuwanoura Fishing Ports are shown in **Figure 34**, where those for T = 800 s, near the second modes, show large phase difference between these two branches, for



#### Figure 34.

The time variations of water surface displacements at Oshima and Kuwanoura Fishing Ports facing Urauchi Bay, where T is the wave period of the incident waves. (a) T = 1600 s; (b) T = 800 s.

Urauchi Bay shows the oscillation resemble to a T-type harbor, with antinodes at two heads and a node at near the bifurcation.

## 6.7.3 The damping processes of oscillations in the T-type harbor and Urauchi Bay

In order to study the damping process of oscillation in the T-type harbor shown in **Figure 31**, we continuously give incident waves to obtain a quasi-steady state of harbor oscillation, after which the incidence of waves is stopped when t = 0.0 s. **Figure 35** shows the time variations of the maximum water level at point A indicated in **Figure 31**, during the damping of harbor oscillation for the first, second, and third modes after t = 0.0 s. The wave period of the incident waves, *T*, for the first, the second, and the third modes are 1150, 650, and 300 s, respectively, based on **Figure 32**. The damping of the oscillation for the second mode is slower than that for both the first and the third modes, because part of wave energy is trapped in the second-mode oscillation between two harbor heads.

Conversely, **Figure 36** shows the time variations of the maximum water level at Oshima and Kuwanoura Fishing Ports facing Urauchi Bay shown in **Figure 1**. The wave period of the incident waves, *T*, is 1600 s for near the first mode, and 720 s for the second mode, based on **Figure 33**. The first-mode oscillation remains longer than the second-mode oscillation, which is not applicable to the T-type harbor mentioned above. Although future work is required to make this reason clear, we can tell the following difference between an actual bay and a typical T-type harbor:



Figure 35.

The time variations of the maximum water level at point A in the T-type harbor shown in **Figure 31**, for the harbor oscillation of the first, the second, and the third modes.



#### Figure 36.

The time variations of the maximum water level at Oshima and Kuwanoura Fishing Ports facing Urauchi Bay shown in **Figure 1**. The wave period of the incident waves, T, is 1600 s for near the first mode, and 720 s for the second mode, based on **Figure 33**.

the width, as well as the still water depth, of the actual bay is not uniform; the shape of the actual bay is curving at some angle.

# 7. Countermeasures against meteotsunamis

## 7.1 The real-time prediction of meteotsunami generation

# 7.1.1 The application of an inverse analysis

We discuss disaster measures against meteotsunamis, generated to propagate toward the west coasts of Kyushu. In order to predict the generation and propagation of meteotsunamis in real time, it is necessary to obtain atmospheric-pressure variation far from Kyushu. If we know the sites, concerning the generation of meteotsunamis through atmospheric-pressure variation, the valuable information on atmospheric pressure is restricted, such that the following inverse analysis is available:

- a. We give some atmospheric-pressure variation at a site, to generate numerical simulation for atmosphere in a huge area including the Asian Continent, the Indian Ocean, and East China Sea, with a typical atmospheric condition for each season.
- b. If an atmospheric-pressure wave appears over East China Sea, we give the atmospheric-pressure wave at the sea surface as an external force, to obtain the amplitude distribution of long waves along the west coasts, as well as the islands, of Kyushu, by applying the numerical model based on Eqs. (1)–(3).
- c. We repeat the abovementioned calculation process for various conditions on atmospheric pressure, with atmospheric-pressure variation at different sites.
- d. Using the results, we analyze inverse problems, where we give the distributions of long-wave amplitude, observed by, for example, the nationwide ocean wave information network for ports and harbors (NOWPHAS) conducted by the Ministry of Land, Infrastructure, Transport and Tourism, at the coasts of Kyushu, with the corresponding atmospheric-pressure conditions, to identify the sites in the Asian Continent and the Indian Ocean, which concerns the generation of meteotsunamis in East China Sea, through atmospheric-pressure variation.

According to the real-time variation in atmospheric pressure at the important sites, we can pick up bays and ports, which involve the risk of meteotsunami attack, to make adequate preparations for the meteotsunamis over a few days.

Conversely, we can also utilize a pattern recognition system for atmosphericpressure distributions, instead of the inverse analysis, to exemplify dangerous atmospheric-pressure patterns.

# 7.1.2 Prediction for the amplitude of long waves using atmospheric pressure above East China Sea

We can predict approximate values for meteotsunami parameters, including long-wave amplitude, based on real-time variation in atmospheric pressure at several sites in East China Sea. If we obtain atmospheric-pressure data from barometers at plural islands, such as Danjyo Islands and Uji islands, shown in **Figure 5**, far from the west coasts of Kyushu, we can imagine the propagation direction of atmospheric-pressure waves and predict the possible largest long-wave amplitude H in East China Sea, by applying the proposed Eq. (10). It is, however, difficult to place barometers at several islands, including uninhabited islands, far from the main island of Kyushu, and the maintenance of the barometers, with sustainable data transfer units, is a hard task. As long as we obtain time variation in atmospheric pressure only at one site, we can predict the possible largest amplitude H, by applying Eq. (10), although the accuracy of H is low, for the propagation direction of the atmospheric-pressure waves is not clear.

If fishing cooperatives and town offices obtain GPV atmospheric-pressure data, presented by JMA, to find out an atmospheric-pressure wave traveling east, they can predict the propagation direction, as well as the possible largest amplitude, of long-waves in East China Sea, where the accuracy of the predicted parameters is improved using Eqs. (8) and (9). It is important to catch every occurrence of large secondary undulation easily, even though both predictive accuracy and hitting ratio are relatively low. The fishing cooperatives and town offices, where the simple derivation process of Eqs. (8)–(10) is preferably understood, should be aware of the importance of the daily monitoring for variation in atmospheric pressure as a routine work.

# 7.2 Structural measures

The following structural measures against meteotsunamis are useful, depending on conditions including bay shape and water depth distribution:

- a. Breakwaters are raised for ports with experience of large harbor oscillation, where several dozen centimeters may be enough. In case high breakwaters work against the loading of fishes and cargos, lockages of less than 1 m in height are suitable.
- b. The bay width is narrowed with jetties, to protect ports and towns at bay heads, without inconvenience for daily steerage. It should be noted that the flow velocity, due to not only meteotsunamis but also tides, between the jetties may be larger, resulting in seabed scour, and that wave energy may be trapped behind jetties, leading to water surface oscillation prolonged in the bay.
  Furthermore, some device is required to advance seawater exchange, for part of the bay is occlusive. If the district to be protected is a narrow area, a water gate between two jetties is effective.
- c. Permeable breakwaters with impounding reservoirs are constructed for coasts at high risk of overflow.
- d. Fishery facilities are built, or moved, to adequate places, for corves etc., located near a node of harbor oscillation, may be flown away owing to flow of large velocity. The fish that got away is always big. The right places should be determined considering both water level and flow velocity, based on the characteristics of harbor oscillation in each bay or port.
- e. Both drainage pipes and street gutters are designed to prevent inundation due to the intrusion of seawater into the residential area through the pipes and gutters. Although the walls of the castle, which is a world heritage, in Galle, Sri Lanka, rejected the tsunamis caused by the 2004 Indian Ocean earthquake, the seawater entered the inside of the walls through drainage pipes, leading to the flood.

f. River banks are constructed in consideration of meteotsunamis ascending rivers, as well as downflows due to heavy rain. The wave height of nonlinear tsunamis due to a submarine earthquake increases, when they travel upstream along a river with relatively narrow width, depending on the mouth shape of the river, according to the numerical results from the three-dimensional calculation [19].

# 7.3 Nonstructural measures

The coastal structures are permitted to be built considering cost effectiveness, nearshore environment, etc., such that nonstructural measures, including evacuation and preparation against meteotsunamis, are necessary as follows:

- a. When a meteotsunami is predicted to be generated in the ocean, fishing boats and vessels are put offshore, if it is not stormy; if it is possible, they are put up on the land. Otherwise, mooring ropes should be tied firmly to prevent the flowage of fishing boats. If the ropes are too short, boats and vessels may be damaged when they collide with seawalls, or go on shore, owing to water level rise and onshore currents. Conversely, when the water level lowers, boats are hung by mooring ropes, as sketched in **Figure 37**, and they become upsidedown, after which they are waterlogged as the water level rises. Note, however, that if mooring ropes are too long, boats are damaged owing to their collisions, such that bumpers should be attached to both boats and seawalls, unless the mooring positions are not moved to calm spots in harbor oscillation. Mooring facilities should be developed for temporary mooring at calm positions against meteotsunamis.
- b. Waterproof tools, such as waterproof walls and sandbags, should be prepared for inundation of architectures including houses, shops, fishery facilities, factories, etc. **Figure 38** shows the examples of waterproof walls, equipped at Kinki Area Seaside Disaster Prevention Center in Osaka Prefecture, Japan.



**Figure 37.** *A fishery boat hung by a mooring rope, as the water level lowers owing to meteotsunamis.* 



#### Figure 38.

The waterproof walls equipped at Kinki Area Seaside Disaster Prevention Center in Osaka Prefecture, Japan. The wall panels can be carried and set at places where waterproof is supposed to be required. In case shown in the figure, the panels are piled up in front of the doors, using frames.

c. It is most important to notify inhabitants immediately that meteotsunamis are predicted to approach the coasts, using a community wireless system and speakers, or door-to-door visits. The prediction of disasters including meteotsunamis is probabilistic, commonly without high accuracy in their parameters, such that education to increase public awareness about disaster prevention is essential. It is crisis management that covers all the cases, whether the boy who cries wolf is right or not.

# 8. Conclusions

First, the generation and propagation of long ocean waves due to the atmospheric-pressure variation were simulated using the numerical model based on the nonlinear shallow water equations, where the atmospheric-pressure waves of four pressure-profile patterns traveled eastward over East China Sea, as well as the atmospheric-pressure waves that caused the large harbor oscillation in Urauchi Bay on February 25, 2009. The wave height of the long waves increased as the moving velocity of the pressure-recovery point was close to that of the long ocean waves. Before the oscillation attenuation in Urauchi Bay, the incidence of long waves can continue owing to an oscillation system generated between the main island of Kyushu and Okinawa Trough.

Second, the simple estimate equations were proposed to predict both the wave height and wavelength of severe meteotsunamis, using observed or GPV atmospheric-pressure data concerning the pressure profile of atmospheric-pressure waves or the recovery rate of atmospheric pressure in the ocean, without complicated calculation. The estimated values for both the wave height and wavelength of the long ocean waves showed good agreement with the corresponding computational data.

Third, numerical simulation was generated for the oscillation in the harbors of various shapes. The amplification factor at the head of the L-type harbor for the second mode increased, as its bending position was nearer to the harbor mouth. As

the narrowed area of the I-type harbor was located nearer to the harbor mouth, the amplification factor at the head for the first mode decreased, while that for the second mode increased. The C-type harbor showed the amplification depending on the position with the phase difference between the waves coming through two mouths. When the I-type harbor has the seabed crest, the amplification factor at the head for the first mode was larger than that for the second mode, while the reverse was true, when the I-type harbor has the seabed trough. Although the oscillation in Urauchi Bay had the second mode specific to T-type harbors, where antinodes appeared at their two harbor heads, future work is required to make clear the reason why the damping processes were different between Urauchi Bay and the T-type harbor.

Finally, the disaster measures were discussed against meteotsunamis, generated to propagate toward the west coasts of Kyushu. The methods of real-time prediction for meteotsunami generation were proposed using the inverse analysis, as well as the simple prediction equations, after which both the structural and the nonstructural measures against meteotsunamis were summarized.

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