Preliminary Simulation Study of Ship Evacuation in the event of Tsunami Attack in the Seto Inland Sea, Japan.

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Abstract: The probability of the Nankai and Tonankai earthquakes reoccurring in the Nankai Trough off Shikoku, Japan, is estimated at over 50 percent in the 30 years from January 1, 2008. A tsunami caused by such an earthquake attacks the Japanese coast by generating not only raised sea level but also strong horizontal flow. Ships in a bay may be forced to move by the currents and unexpected phenomena may occur such as the impact of large forces on a pier, uncontrollable lateral motion, collision of a ship with the breakwater and drifting and grounding. The purpose of this paper is to minimize tsunami disaster for ships in the Seto Inland Sea. In this study, we carried out several types of simulations of ship evacuation from tsunami attack in the Seto Inland Sea. Two main conclusions can be drawn from these simulations. firstly, a ship can be evacuated safely to the evacuation area, and secondly, a ship can withstand the tsunami by anchoring in the evacuation area.

Keywords: Tsunami attack, ship evacuation, Nankai and Tonanka earthquakes

１. Introduction

Nankai and Tonankai earthquakes of magnitude 8.0 have occurred intermittently in the Nankai Trough off Shikoku, Japan over the past 1500 years. Fig.1 shows the location of the Nankai Trough. Examples of such earthquakes are Keichou in 1605 with a magnitude of 7.9, Houei in 1707 (M8.6), Tonankai in 1944 (M8.4), and Nankai in 1946 (M8.4). As of January 1st, 2008, the probabilities of the Nankai and Tonankai earthquakes reoccurring in the next 30 years are estimated to be 50% and between 60% and 70%, respectively. A tsunami caused by such an earthquake along the Japanese coast would generate a rise in sea level and also strong horizontal flow. Ships in a bay may be forced to move by the currents, possibly causing unexpected phenomena to occur such as the impact of large forces on a pier, uncontrollable lateral motion, collision of ships with the breakwater and drifting and grounding.

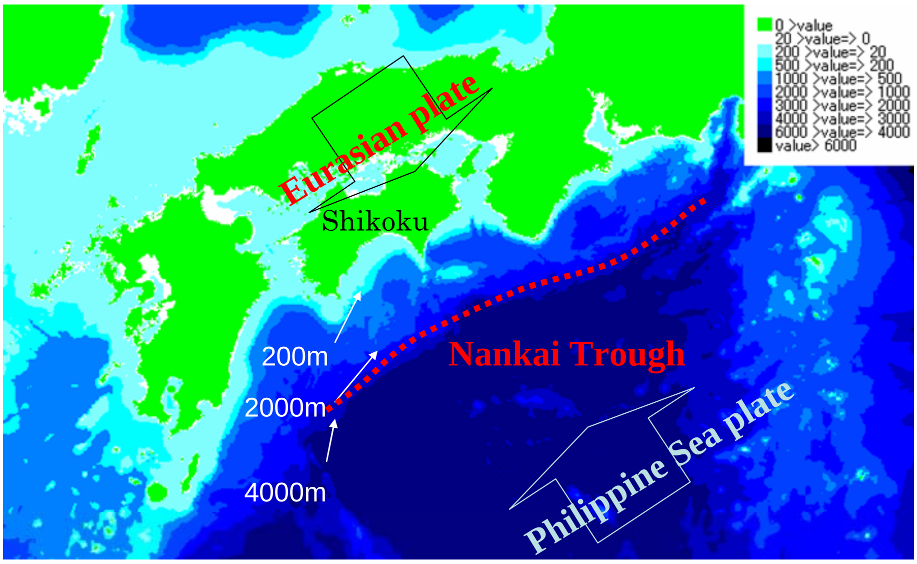

Fig. 1 Location of Nankai Trough off Shikoku, Japan

For these reasons, various studies have been conducted on the effect of a tsunami on ships, especially in Osaka Bay$^{1)}$, which has an important energy plant along its shore. However, no concrete examination has been made in the Seto Inland Sea, west of Osaka Bay. The arrival time of a tsunami in the Seto Inland Sea is later than in Osaka Bay. Moreover, the effect of tsunami is small in this location. However, the shipping traffic in the Seto Inland Sea is heavier than in Osaka Bay and there is a variety of ships such as dangerous object transport ships, fishing boats and ferries. Therefore, examination of tsunami attacks in the Seto Inland Sea is important in order to minimize their impact. We carried out several types of simulation of ship evacuation from tsunami attack in the Seto Inland Sea and show the possibilities for ships to evacuate to the evacuation areas and to withstand tsunami during anchoring.

2. Types of ships

Typical ships that navigate the Seto Inland Sea are described in Table 1 and these were used in this study.

Table 1. Types of ships in the Seto Inland Sea

Category	Type of ship	Length between perpendiculars	Breadth	Draft	Block coefficient
499 ton	Fisher	61.1 m	10.4 m	4.6 m	0.573
3000 ton	Chemical Tanker	106.6 m	16.1 m	6.7 m	0.781
10,000 ton	RO-RO Ship	162.0 m	23.1 m	7.8 m	0.668
160,000 ton	VLCC	325.5 m	58.0 m	10.4 m (*)	0.818

* The full load draft is 20.8 meters. However, the ship was assumed have a light load it is not possible to sail with a full load in the shallow water area.

3. Evacuation areas and evacuation routes

If a tsunami arrives in the Seto Inland Sea, the ships must evacuate to the evacuation areas as soon as the Meteorological Agency issued tsunami warnings. Fig. 2 shows the evacuation areas and the evacuation routes.

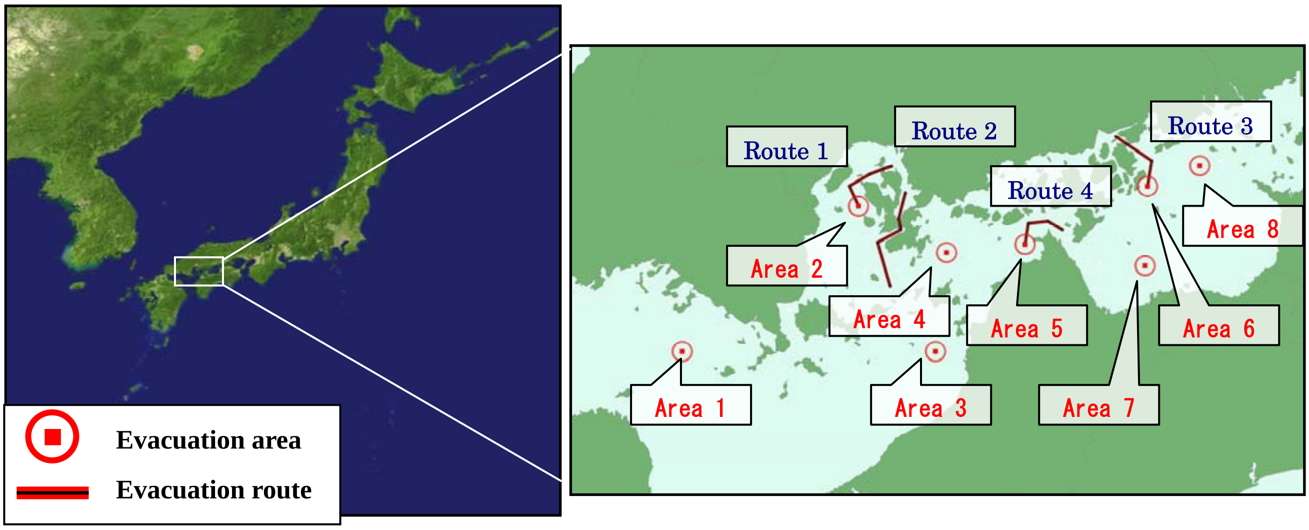

Fig. 2 Evacuation areas and evacuation routes in the Seto Inland Sea, which is surrounded by the islands of Honshu, Shikoku and Kyushu

4. Tsunami and tidal currents simulation

4-1 Tidal currents simulation

Simulation of tidal currents was compared to from the prediction of currents in the Tsurishima Suido Traffic Route to the northwest in Matsuyama in the tide table (version 2004)[2)]. The maximum of the northeast currents in this traffic route was 3.1 kt (1.59 m/s), and southwest currents was 3.0 kt (1.54 m/s). These two maximum flow velocities occurred during the same day, October 16th, 2004, and hence the simulation was conducted on this day. This simulation was made using the Princeton Ocean Model (POM). This model was appropriate for two-dimensional calculation (perpendicular one layer) to suit the tsunami model. The simulation period was 36 hours from 07:00 October 15th to 19:00 October 16th, 2006. Using this simulated tide level, boundary conditions for a 50-meter-subgrid were created. A time period from 30 hours from 13:00 October 15th to 19:00 October 16th, 2004, was calculated in 0.5 second time steps. Although the phase of the calculated values of flow velocities_was slightly early, the observed tide level was well reproduced. The southwest current reaches a maximum at approximately 14.5 hour into the simulation and the flow velocities were found to be approximately 1.0-1.5 m/s, slightly slower than the value of 3.0 kt (1.54 m/s) given in the tide table for 03:25 on October 16th. The northeast currents become a maximum at approximately 21 hours into the simulation. The flow velocities reached approximately 1.5 m/s at 21:00 and this is close to the value of 3.1 kt (1.59 m/s) given in the tide table for 10:00 on October 16th. The results showed that the tide model was hence verified and works well.

4-2 Tsunami currents simulation

4-2-1 Mathematical model of the tsunami

Tsunami can be described by both continuity and momentum conservation equations based on non-linear long wave theory, which provides a uniform distribution of horizontal velocity in the direction of water depth using the coordinate system shown in Fig. 3.

$$\left.\begin{aligned}
&\frac{\partial \eta}{\partial t}+\frac{\partial M}{\partial x_0}+\frac{\partial N}{\partial y_0}=0\\
&\frac{\partial M}{\partial t}+\frac{\partial}{\partial x_0}\frac{M^2}{D}+\frac{\partial}{\partial y_0}\frac{MN}{D}+gD\frac{\partial \eta}{\partial x_0}+\frac{\tau_x}{\rho}=0\\
&\frac{\partial N}{\partial t}+\frac{\partial}{\partial x_0}\frac{MN}{D}+\frac{\partial}{\partial y_0}\frac{N^2}{D}+gD\frac{\partial \eta}{\partial y_0}+\frac{\tau_y}{\rho}=0
\end{aligned}\right\}\quad (1)$$

where

h ::still-water level

η : elevation above still-water level

D : depth of water ($=h + \eta$)

x_0,y_0 : coordinate system

ρ : density of water

τ_x, τ_y : sea bottom friction in the x_0,y_0 direction

M, N : x_0,y_0 direction flow volume flux

t : time

g : gravity acceleration

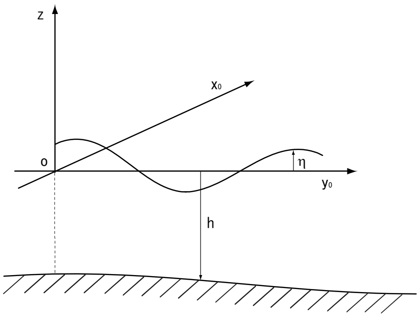

Fig. 3 System of coordinates for tsunami calculation

４-２-２ Simulation of the tsunami

Using equation (1), we simulated a tsunami caused by earthquakes in the Nankai Trough, assuming a Tonankai and Nankai linkage type earthquake. The Central Disaster Prevention Council predicts that the tsunami which has the potential for the most serious damage will be generated by this type of earthquake[3]. Table 2 shows the fault model for the Nankai and Tonankai earthquakes used in this study. The initial values for the tsunami equation were based on this fault model. The grid interval adopted was 50 m in the western Seto Inland Sea and the period over which the model was calculated was nine hours from earthquake occurrence. The value of the seabed friction coefficient was calculated based on Manning's roughness coefficient, and an invasion to land of tsunami was neglected.

Table 2 Fault model of earthquake

	Nankai earthquake	Tonankai earthquake
The origin of fault plane	N 32°54’ 57” E 135°36’ 1”	N 33°37’ 8” E 137°13’ 47”
The amount of fault slip [m]	9.45	7.05
Fault length [m]	150000.0	150000.0
Fault width [m]	120000.0	70000.0
Fault strike [degree]	250.0	250.0
The angle of fault inclination [degree]	20.0	10.0
The direction of fault slip [degree]	117.0	127.0
The depth of fault plane [m]	1000.0	10000.0

４-３ Verification of tsunami simulation results

From the results of the tsunami simulation and tidal currents calculation, the maximum horizontal flow of the tidal currents was found to be stronger than tsunami currents in the western Seto Inland Sea. However, in some channels such as the Hayase Seto, the tsunami currents are stronger than the tidal currents. Ships need to take care in these areas. The maximum magnitude of sea level change (the absolute value maximum of displacement from Standard sea level (T.P.)) is larger for tidal currents then tsunami currents. Moreover, the deviation between mean sea level and the highest and lowest level of the tide respectively is larger than the elevation of the tsunami.

5. Ship evacuation simulation

5-1 Mathematical model

If a tsunami attacks inside a harbor and the inner part of the bay is not narrow or the depth is not suddenly changing, the main currents generally flow in a horizontal direction. The coordinate system used in the ship maneuvering simulation is shown in Fig. 4. It shows a relative coordinate system where the center point is the center of gravity of the ship. The longitudinal, lateral and downward directions on the ship are the x, y and z-axes respectively. The ship motion equation is given in equation (2).

$$\left.\begin{aligned}
&(m+m_x)\dot{u}-(m+m_y+X_{vr})vr \\
&-(u_{c0}\sin\psi-v_{c0}\cos\psi)(m_y-m_x+X_{vr})=X_H \\
&(m+m_y)\dot{v}+(m+m_x)ur \\
&-(v_{c0}\cos\psi+v_{c0}\sin\psi)(-m_y+m_x)r=Y_H \\
&(I_{zz}+J_{zz})\dot{r}=N_H
\end{aligned}\right\} \quad (2)$$

where

m : mass of the ship

m_x , m_y : added mass (virtual mass) of the ship in x, y directions

I_{zz} : mass moment of inertia of the ship about the z direction

J_{zz} : added mass moment (virtual mass moment) of inertia of the ship about the z direction

u , v : velocity components in the x, y directions

u_{c0} , v_{c0} : velocity components of the tsunami in the x, y directions

r : rate of turn about the z direction

ψ : angle of turn

$\dot{u}$, $\dot{v}$, $\dot{r}$: u , v and r differentiated in time

X_H , Y_H , N_H : longitudinal and lateral force, and the moment acting on the ship about the z direction

Moreover, about X_H, Y_H and N_H, flow from the tsunami that pour into the hull is flow from a constant course in the neighborhood of hull The shallow water effect in Y_H and N_H was considered, because in the harbor, the distance between the seabed and the bottom of the ship is smaller than the draft.

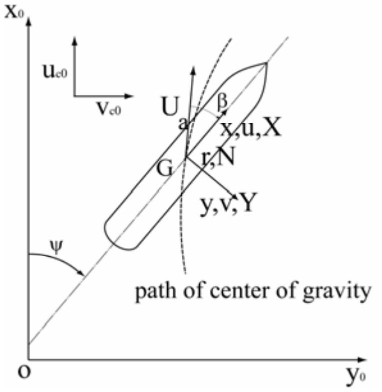

Fig. 4 Coordinate system of ship maneuvering simulation

$$\left.\begin{aligned}
X_H &= \frac{\rho}{2} L d U_c^2 C_{DX}(\theta_c) \\
Y_H &= \frac{\rho}{2} L d U_c^2 C_{DY}(\theta_c, H/d) \\
N_H &= \frac{\rho}{2} L^2 d U_c^2 C_{DN}(\theta_c, H/d) + N_r(r, H/d)
\end{aligned}\right\} \quad (3)$$

where,

L, d, H : ship length, draft and water depth
U_C, θ_C : relative flow velocity and direction
ρ : density of sea water
C_{DX}, C_{DY}, C_{DN} : longitudinal and lateral drag of current coefficient and current moment coefficient
N_r : moment with turning movement

We solved differential equation (3) and calculated the time history of ship motion, because the magnitude and direction of flow (U_C, θ_C) change over time. We executed a ship-maneuvering evacuation simulation under the influence of currents. The combined current was the horizontal flow calculated as the combination of both tidal and tsunami currents. The ship in this simulation was navigated to the preset evacuation course. Also, in these simulations we implemented auto-preservation of the route by using a simple auto pilot function, as shown in equation (4). The target route is the baseline that directly joins the waypoints and the angle of target direction is the angle of this baseline.

$$\delta^* = -C_0 \Delta y - C_1 \Delta \psi - C_2 \Delta r \qquad (4)$$

Where

δ^* : rudder angle
Δy : side deviation between actual route and target route
$\Delta \psi$: angle deviation between actual and target direction
r : rate of turn
C_0, C_1, C_2 : integral coefficient, proportionality coefficient, differential coefficient

5-2 The result of the evacuation navigation simulation

In evacuation route 1 (Fig. 2), the ship navigates through Nasami Seto from Hiroshima Harbor to the evacuation area. Fig. 5 shows the navigating locus of a 3000 ton RO-RO ship obtained by the simulation. While proceeding to the evacuation area, the ship encounter the maximum flow caused by the tsunami and tide at point1-2 as shown in Fig. 5. Moreover, Fig. 6 shows the time history of the velocity of flow and the water level at point 1-2. Time is represented by the arrow, which is measured from the occurrence of the earthquake until the maximum flow in Fig. 6. The maximum velocity of both tsunami and tidal currents were assumed to impact on a ship. It takes several hours for tsunami velocity to peak. If a tsunami occurs, a ship must evacuate to an evacuation area immediately. If the decision to evacuate is made late, the ship will face the strongest currents caused by the tsunami.

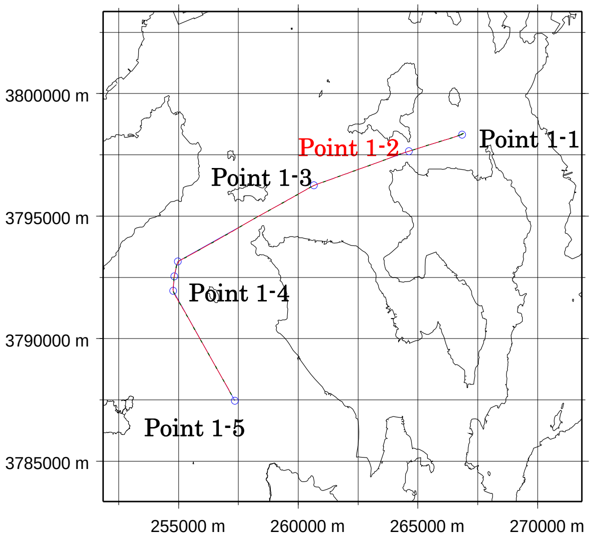

Fig. 5 Track of RO-RO Ship (3,000 ton category) through the evacuation route 1.
(blue circles: target route; blue line: target course; red line: simulated course)

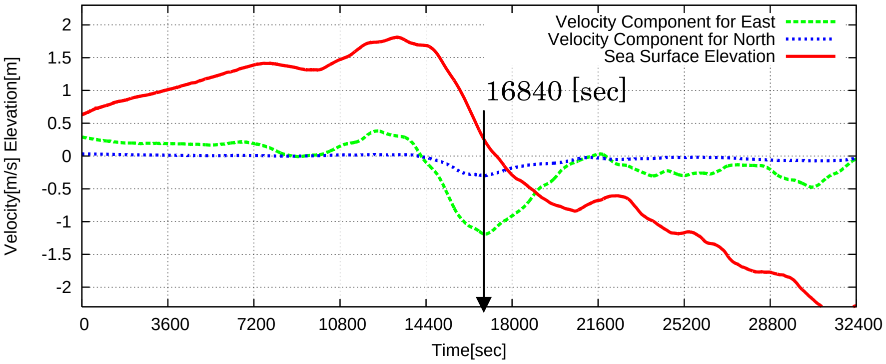

Fig. 6 Time history of water level and flow velocity due to the tsunami and tidal currents at point 1-2

Fig. 7 and Fig. 8 show that the angle of the direction of the ship and the rudder angle controlled by the auto pilot respectively. Figs. 6 and 7 indicate that the ship navigated along the proper course and the direction is stable. These results show that the evacuating ship was only slightly affected by the tsunami and tide. Fig. 8 shows that the change in the rudder angle is small. Similarly, this simulation was also carried out on ships of sizes approximately 499, 3 000, 10 000 and 160 000 ton and similar results were obtained.

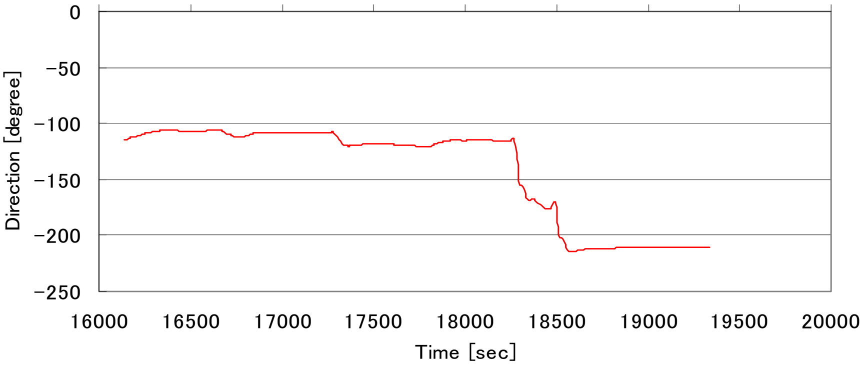

Fig. 7 Time history of direction of RO-RO Ship (3,000 ton category) through the evacuation route 1

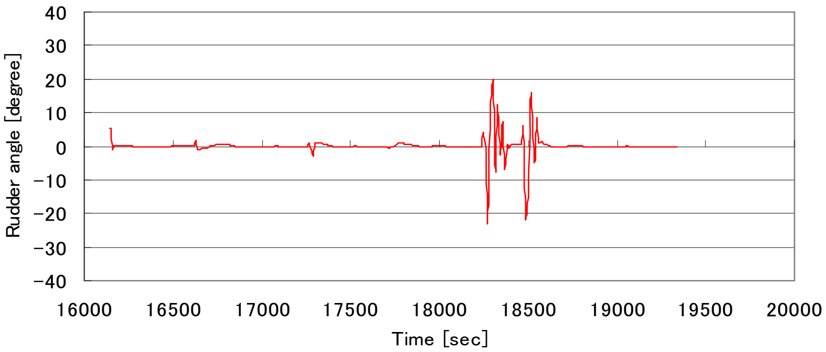

Fig. 8 Time history of rudder angle of RO-RO Ship (3,000 ton category) through the evacuation route 1

6. Ship anchoring simulation

Simulations of ship anchoring under tsunami attack were performed. It was assumed that the ship anchored at the evacuation area (Fig.2) before the arrival of the tsunami. We carried out a single anchoring simulation as a basic study. The simulation was carried out by “Lumped Mass Method” as shown in Fig. 10. The “Lumped Mass Method” expresses a cable and an anchor as many mass points and springs. The equations of motion for each mass point were solved and their motions and tensions were obtained.

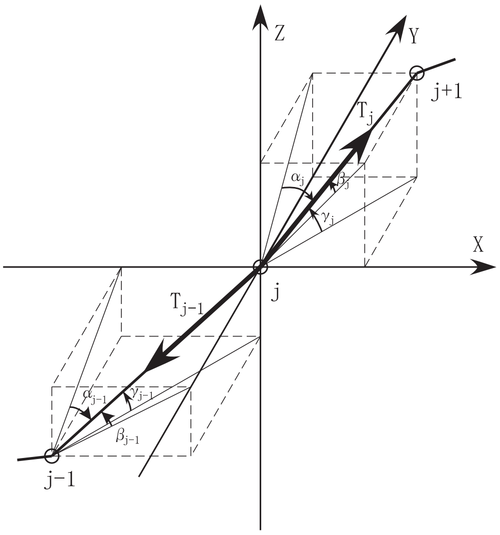

Fig. 10 The chain motion calculation modeled by the Lumped Mass Method

The initial conditions for the simulation were set using the processes of actual anchoring in the sea. Firstly, the anchor is released from the ship at the anchorage point and then lands on the surface of the seabed. Then the ship goes astern at the same time as it drops the chain. A chain is dropped from the “bell-mouth” which is the hole located on the bow of ships. We used the following equation (5) for the length of the chain.

$$L = 4D + 145 \quad (5)$$

Where

L: Length of chain.
D: Depth at anchorage area.

The two initial conditions of the chain used in the simulations were:

1. The chain was located vertically below the bell-mouth.
2. The chain was located horizontally with the anchor.

It is assumed that the seabed is flat. The flow of tsunami and tidal current are modeled as one layer. The coefficients used for the ship anchoring simulations are shown in Tables 3, 4 and 5.These parameters were referred from the references[4]

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Table 3 Values of parameters of anchor and anchor chain

3000t	Diameter of chain	50[mm]
	Mass of chain per unit length	54.7[kg/m]
	Mass of anchor	3000[kg]

Table 4 Coefficients of anchor holding power used for simulation

Type of seabed	Sand
Coefficient of anchor	7
Coefficient of chain	2

Table 5 Coefficients of parameters used for simulation.

Coefficient of added mass in normal direction	1.98
Coefficient of added mass in tangential direction	0.20
Coefficient of drag in normal direction	2.18
Coefficient of drag in tangential direction	0.17

The simulation was carried out when the flow of velocity is maximized by the tsunami and tidal currents at the same time in the evacuation area; because we assume that this scenario is one of the most severe. We assumed that the initial position of the ship was at the evacuation point and direction against the flow of tidal currents. Fig. 11 shows the time history of the elevation and velocity of flow due to both the tsunami and tidal currents used in the anchoring simulation. Figs. 12 and 13 in the Appendix show the results of the anchoring simulation.

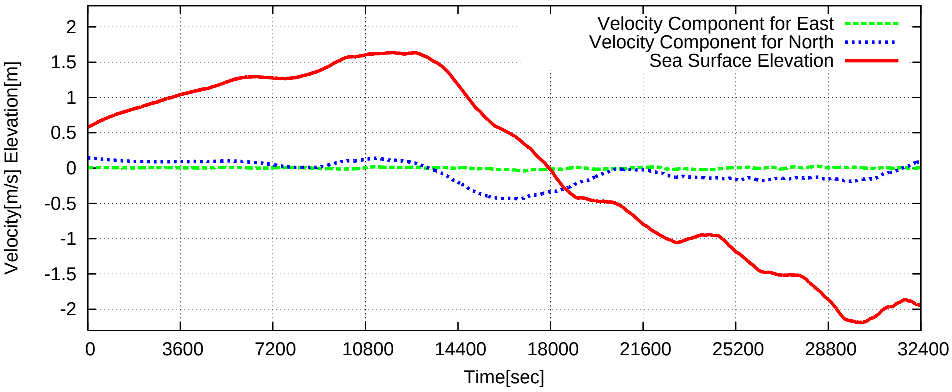

Fig. 11 Time history of elevation and velocity under the tsunami and tidal currents at the area 2

In this evacuation area the tidal currents change direction from northward flow to southward. The velocity of flow was both increased and decreased during the course of the tsunami event; however the absolute value of the velocity of the tsunami currents were lower than that of the tidal currents. Therefore, the tidal currents had greater effect on the motion of the ship than the tsunami. In particular, the flow direction changed only in the south and north directions. Therefore, the anchor chains also only moves in the north-south direction on seabed. The anchor did not drag, and the ship changed direction slightly along tidal currents. As a result, it is not difficult for the ship to anchor under tsunami and tidal condition in this evacuation area. However, the officers have to be careful to anchor in other areas with small tidal currents and large tsunami currents. The tsunami currents change direction in the short time. In the case of slow tidal currents, the ship will be forced into complex motion by the reversal of tsunami currents. This may cause the chain to become twisted.

7. Conclusion

In this study, we have evaluated the effect of tsunami currents generated by Nankai and Tonankai earthquakes and tidal currents on four categories of ships (499 ton, 3,000 ton, 10,000 ton, 160,000 ton) within the Seto Inland Sea, Japan.

From the results obtained in these investigations, the following conclusions were reached:

(1) The tidal currents are stronger than tsunami currents in the Seto Inland Sea.
(2) A ship in the Seto Inland Sea can be successfully evacuated from tsunami attack, even if the ship encounters the maximum flow caused by the tsunami and tide.
(3) The probability of dragging of anchor is low. A ship can be anchored safely in the evacuation area.

There are still many areas to be researched in relation to this study:

(1) The validity of these evacuation routes and areas needs to be verified by experts in the field.
(2) In this simulation, the external forces acting on a ship were tsunami and tidal currents, and winds and ocean waves were neglected. Ship behavior needs to be modeled using all external forces.
(3) We need to assess the accuracy of the ship anchoring simulation by observation.
(4) The future research regarding to twisting of the chain on anchoring system is required.
(5) Heavy traffic may become a serious problem if many ships need to evacuate from tsunami attack. Therefore, further study into seaborne traffic along the evacuation routes is required.

In conclusion, this paper performed a preliminary series of simulations of the effect of tsunami attack on a ship. Based on this and future research, the understanding of the effects of tsunami attack on ships can be advanced and appropriate safety measures constructed.

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