Guidelines and considerations for ship evacuation from a tsunami attack

Eiichi Kobayashi
Graduate School of Maritime Sciences, Kobe University
Kobe, Japan

Syunichi Koshimura
Graduate School of Engineering, Tohoku University
Japan

Shouta Yoneda
Imabari Shipbuilding Co.,Ltd.
Japan

Nobukazu Wakabayashi
Graduate School of Maritime Sciences, Kobe University
Kobe, Japan

Abstract

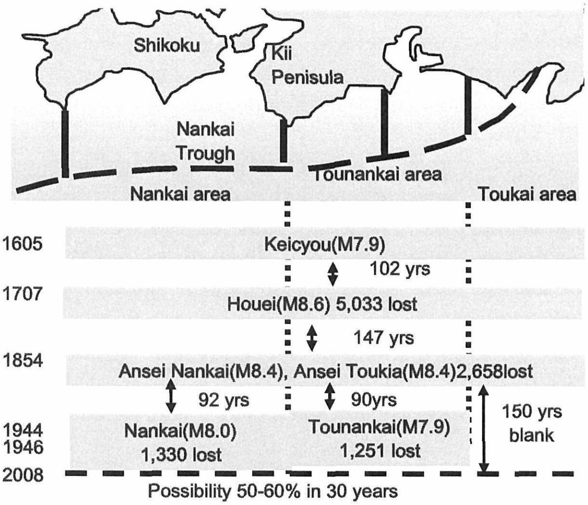
Earthquakes have continuously occurred along the Nankai trough off Kii Peninsula in Japan for more than 1000 years. The tsunamis generated by these earthquakes reach Osaka Bay within approximately one hour of the earthquake. The tsunami causes the slow phenomenon of coming and going of the horizontal water flow, and the rise and descent of the water level in the Osaka Bay. Many oil-related facilities, power plants and petrochemical complexes are located in the landfill area along the Osaka Bay coast, and many cargo vessels transporting hazardous materials navigate the bay. Such ships should be moved outside the port area in the event of an earthquake and a tsunami is expected. However, specific procedures for such evacuation measures have not been developed. In this study, evacuation guidelines for an LNG carrier, representative of a hazardous cargo carrier, were considered in the case of the ship entering Sakai Senboku Port, where many power plants and chemical complexes are located.

1 Introduction

Large earthquakes, such as Keichou in 1605 with a magnitude of M7.9, Houei in 1707 (M8.6), Tou-Nankai in 1944 (M8.4), and Nankai in 1946 (M8.4), have occurred for at least the last thousand years along the Nankai Trough which is located off the Toukai area, Kii peninsula and Shikoku area in Japan, where the Philippine plate subducts the Eurasian plate, as shown in Fig. 1(Watanabe1985). As of January 1st, 2008, the probability of occurrence of the next Nankai and Tou-Nankai earthquakes in the next 30 years is estimated at 50% and 60% to 70%, respectively (Web site of the Headquarters for Earthquake Research Promotion; http://www.jishin.go.jp/main/choukihyoka/kaikou.htm). The tsunami that will be generated by such earthquakes will arrive at Osaka Bay within one and a half hours after the earthquake occurrence. The general characteristics of tsunamis in Osaka Bay are the receding and approaching of the horizontal water flow associated with the sea surface slowly rising and falling.

There are also numerous petroleum, power and chemical plants on the reclaimed land along the coast of Osaka Bay. In particular, there are key industries such as petrochemical refineries, factories, power stations, and their associated industries, companies and facilities in the adjoining area of Sakai-Senboku Port, which runs 10 km north to south, 10 km east to west, and covers an area of 9000 ha. The port is a particularly important harbor, and it extends over Sakai City, Takaishi City and Izumiootsu City; numerous ships enter the port transporting raw materials that are hazardous.

Fig. 1 Historical occurrence of earthquakes along the Nankai Trough.



When an earthquake occurs, and a tsunami attack is expected, ships are basically required to evacuate outside those ports. However, specific procedures for ship evacuation for these areas have not yet been developed. A ship transporting liquefied natural gas (LNG carrier) and entering the Sakai-Senboku Port area is the focus of this study, and is used as an example of a cargo ship transporting hazardous materials.

Although the depth of the water in the area near Sakai-Senboku port is approximately 12-15 m, a waterway that is 16 m in depth, 300 m in width and 7,000 m in length was built from the central part of Osaka Bay to the LNG berth, because an LNG carrier, which is usually 13 m in draft, must proceed along this waterway due to draft restrictions. In this study, an evacuation procedure for an LNG carrier arriving at or departing from the port in the tsunami attack was investigated.

First, for a situation involving an LNG carrier, the locus and variation of the ship speed was analyzed using automatic identification system (AIS) equipment. Secondly, tsunami simulation around Osaka Bay was performed to elucidate the arrival time, horizontal velocity and elevation at several important points. Furthermore, evacuation times and anchoring performance were discussed using ship-maneuvering simulations. Finally, evacuation guidelines for a tsunami event were investigated from several perspectives.

2 Investigation of LNG locus by AIS

2.1 Installation of AIS

Actual sea traffic conditions of LNG carriers entering at Sakai Senboku port in Osaka Bay were investigated using AIS receiver equipment installed at the Kobe University. The main component of the AIS system, the Euronav AI3000, was used exclusively for receiving AIS data and was connected to a PC by RS-232C serial connection. All AIS data received by the PC were continuously and automatically stored in the hard disk of the PC. That data could be retrieved through the internet and analyzed on another PC at any time. The AIS data-receiving system and the system configuration are shown in Fig. 2. Important AIS data of ships in Osaka Bay can be obtained with relative ease as the installation of onboard AIS systems is now required for all ships of more than 3000 GT on international routes and all domestic ships of more than 500 GT. It is possible to receive static information, dynamic information, and navigation information and some additional data from installed onboard AIS.

Static information includes the vessel's maritime mobile service identity (MMSI), the name of the vessel, radio call sign, ship length, the draft of the ship, the IMO(International Maritime Organization) number, ship width, type of ship, and antenna position. Dynamic information includes the longitude, latitude, time, course, rate of turn, and speed over ground. Navigational information includes the draft of the ship, the destination, and the type of cargo.

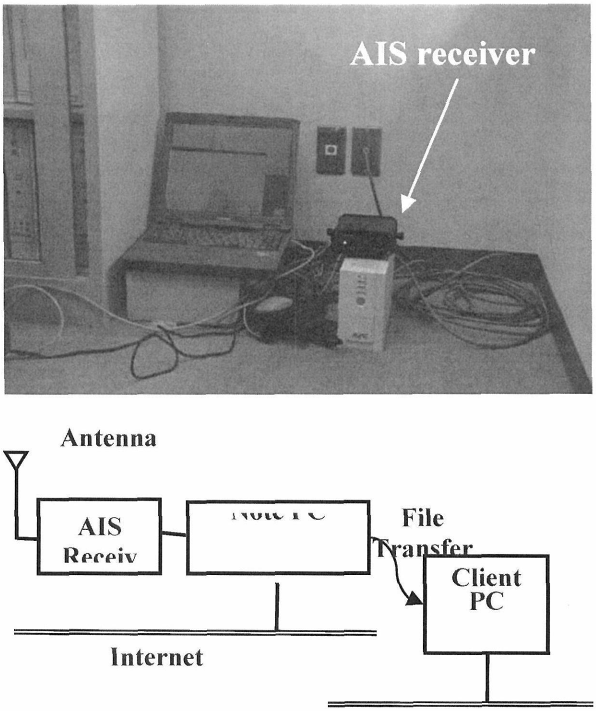


Fig. 2 AIS receiving system.

2.2 AIS Data Analysis

The analysis results of representative LNG's entering and departing from Osaka Bay using the AIS data receiving system are shown in Fig. 3. At the time of arrival in Osaka Bay, after passing through the Kii Channel in a northward direction, the LNG carriers reduce speed to allow the bay pilot at a pilot station 34°10.2"N and 134°5 9.8" E, located in the southern area near the Tomogashima Channel, to board the ship. The ships then increase speed and after passing through the Tomogashima Channel, proceed in a northeasterly direction through the western area of Kansai International Airport Island.

The AIS data obtained for LNG carriers that went through the Hamadera Passage and either docked at or left from the LNG berth were analyzed from July to September 2006. Most LNG ships that passed through the passage were of the 125 km3 type, and were moved to one of four berths. The summarized AIS data analysis shows that three LNG ships passed through the Hamadera Passage every four days.

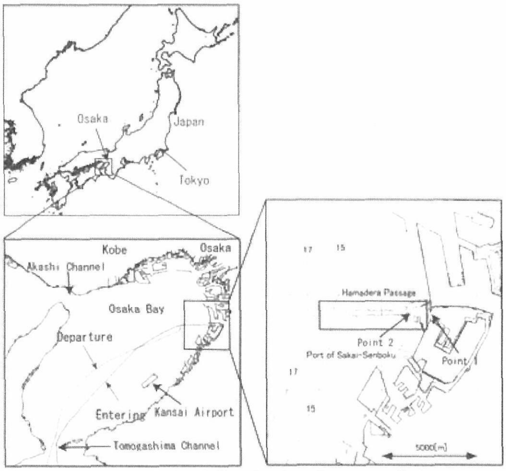


Fig. 3 Ship locus for the Sakai Senboku Port and Hamadera Passage.

3 Simulation model

A tsunami consists of long waves that are generated by the change in seafloor topography caused by an earthquake. Tsunami phenomena can be expressed 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. 4.

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

where

η : elevation from still sea water, t : time, x, y, z : coordinate system, g : gravity acceleration, ρ : density of water, D : depth of water, τ_x, τ_y : sea bottom friction in the x,y directions, M, N : x,y directional volume flux.

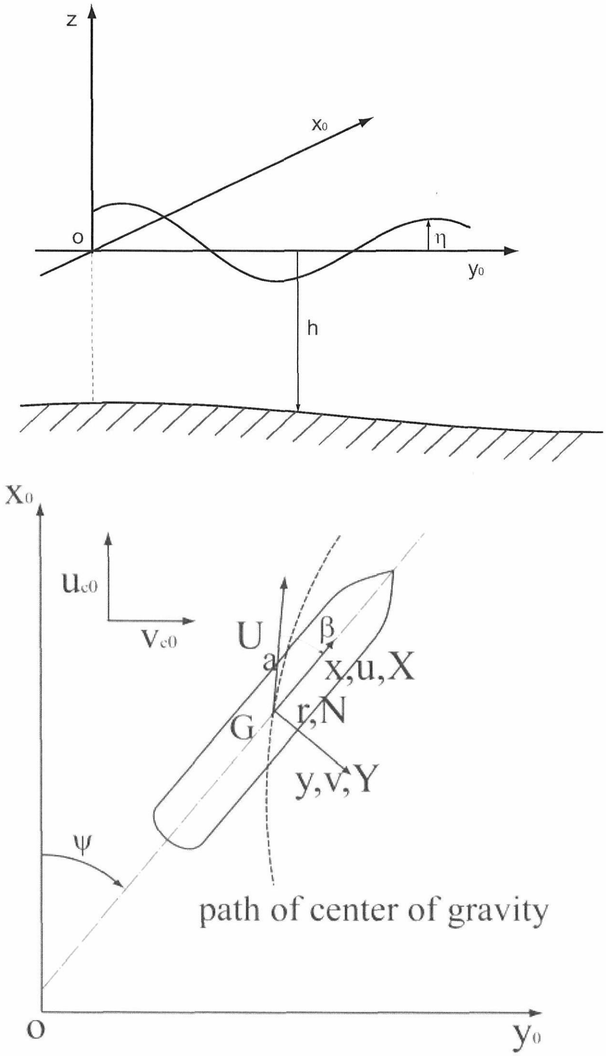


Fig. 4 System of coordinates used for the tsunami calculation (left) and ship maneuvering simulation (right).

Solving the above mentioned equations using the finite-difference time-domain method with 50 m 150 m, 450 m and 1350 m-mesh systems, horizontal velocity components u, v are obtained. Ship maneuvering motions can conventionally be expressed by the following equations using the coordinate system shown in Fig. 4:

$$\left.\begin{array}{l}(m+m_x)\dot{u}-(m+m_y+X_{vr})vr \\ -(u_{c0}\sin\psi-v_{c0}\cos\psi)(m_y-m_x+X_{vr})=X_H \\ (m+m_y)\dot{v}+(m+m_x)ur \\ -(v_{c0}\cos\psi+v_{c0}\sin\psi)(-m_y+m_x)r=Y_H \\ (I_{zz}+J_{zz})\dot{r}=N_H\end{array}\right\} \quad (1)$$

where,

m : mass of the ship,

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

I_{zz} : mass moment of inertia of the ship about the z-axis,

J_{zz} : added mass moment of inertia of the ship about the z-axis,

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

u_{c0}, v_{c0} : velocity components by the tsunami in the x,y direction,

r : rate of turn,

X_H, Y_H, N_H : longitudinal and lateral forces, and the moment acting on the ship.

4 Tsunami calculation

The tsunami simulation was carried out to determine the effect of an event at a representative point along the Osaka Bay coastline using the abovementioned method. Fig.6 shows the elevation of the sea surface and lateral velocity components in easterly and northerly directions at the center of the Tomogashima Channel. Based on these calculations, the water level rises to a peak value of 1 m, the velocity component in the northerly direction becomes 1 m/s, and the velocity component decreases in an easterly direction within approximately 1 hour after the earthquake occurrence.

Fig. 6 shows the time histories for the elevation of the sea surface and the velocity components at the narrow point(Point 1 in Fig. 3) between breakwaters built at the mouth of the Hamadera anchoring area where the Hamadera passage ends. The horizontal velocity increases to 2.5 m/s and the sea surface elevation reaches 1.5 m one hour and forty minutes after the earthquake. The horizontal velocity becomes 4.5 m/s by the time the second tsunami arrives, which is two hours and thirty minutes after the earthquake.

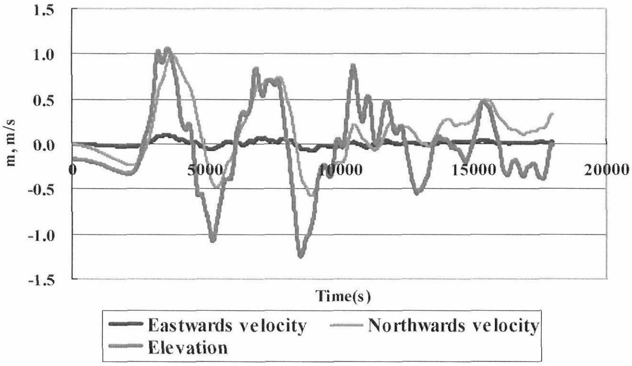


Fig. 5 Computed sea water level and velocity components during a tsunami event in the Tomogashima Channel.

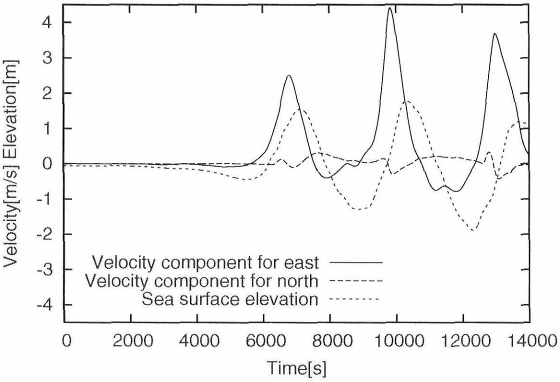


Fig. 6 Computed sea water level and velocity components during a tsunami event at Point 1.

5 Evacuation scenarios

When the next Nankai earthquake occurs, and a tsunami heading toward Osaka Bay is expected, all of the ships in the port should be evacuated to a safety zone outside the port as quickly as possible, where they should be anchored if necessary. The following choices for an evacuation scenario are considered in the event that an LNG carrier enters Osaka Bay after passing through the Tomogashima Channel:

(1) Making a u-turn and proceeding toward the Pacific Ocean after passing through the Tomogashima Channel again.

(2) Going to Harimanada after passing through the Akashi Channel.
(3) Anchoring at an appropriate area in Osaka Bay.

According to the numerous concerns associated with so many ships being evacuated from ports along the coastline of Osaka Bay into the center of the bay at the time of a tsunami event; scenarios for evacuating as many ships as possible from Osaka Bay were examined in this study.

Since a tsunami event affecting Osaka Bay is likely to be associated with slow horizontal flow, and because ships can easily navigate the Tomogashima and Akashi Channels before the arrival of the tsunami, the investigation of evacuation scenarios was carried out according to the following conditions:

(1) A ship's crew recognizes the potential for a tsunami within 10 minutes after the occurrence of an earthquake.
(2) The ships pass through the Tomogashima or Akashi Channels 10 minutes prior to the arrival of the first tsunami at those points.
(3) Ten minutes are required to turn the ships around.
(4) Depending on proximity, evacuation begins by passing through either the Tomogashima or Akashi channel.
(5) Ships anchor themselves unless they are passing through the channels.

Fig. 7 shows the evacuation patterns obtained from investigations using these conditions. A ship in a northward zone after passing through Tomogashima Channel can avoid contact with a tsunami by changing the heading direction by 180 degrees and going south through the channel. When the ship is in a more northern zone, the ship can avoid the tsunami attack by going through the Akashi Channel. When the ship is in the western zone of the Hamadera passage, it can anchor itself at an appropriate position. Conversely, a more detailed investigation is necessary for a ship that enters the Hamadera passage, because the ship could not go anywhere from the passage nor can it change its heading angle in such narrow area.

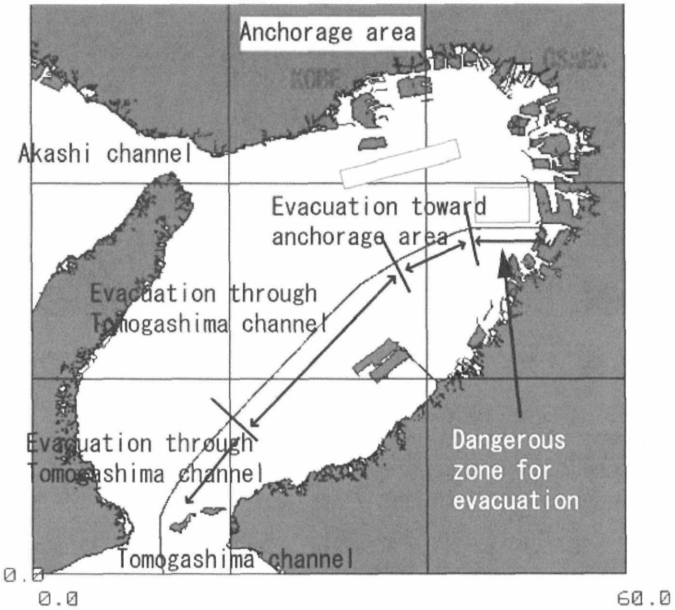


Fig. 7 Evacuation patterns of arrival.

6 Simulation study

An LNG carrier entering the Sakai Senboku Port should initially proceed through the Hamadera Passage, which is 7000 m in length and 300 m in width, with the assistance of four 3000 hp-class tug boats, and berth.

Computer simulations were conducted to determine and evaluate an evacuation scenario under the most dangerous conditions where an LNG carrier, whose principal diminutions are listed in Table 1, is proceeding through the passage. In Case 1, it is assumed that the worst scenario is that the number of tug boats near the berth is insufficient, and it takes 60 minutes after the occurrence of the earthquake to leave the berth. Thus, the LNG ship, moored in the inbound direction, leaves the pier with tugboat assistance, then changes its heading angle in the Hamadera turning basin, before proceeding through the passage in a westerly direction.

In Case 2, it is assumed that the ship moored in the outbound direction rather than the inbound direction, which is the standard procedure at the berth. In this case, it is assumed that it takes 30 minutes to leave the berth, because there is no need to change the heading angle and because additional tugboats are not required for departure.

Table 1 Principal dimensions of the LNG carrier

Length between perpendiculars(Lpp)	270.0 m
Breadth	44.8 m
Draft	10.8 m

The computer simulation results for Case 1 and Case 2 are shown in Fig. 8 and Fig. 9, respectively. For Case 1, the ship drifted slightly to the inner area of the port by the tsunami-generated flow when the ship is turning in the basin.

When considering ship evacuation from a tsunami event, simulations for LNG ship evacuation from Sakai Senboku Port indicate that outbound mooring is preferable to inbound mooring. However, despite having tugboat assistance, it can be dangerous to attempt turning in-situ in a narrow area with a full load of hazardous cargo to achieve outbound berthing. Further investigations focus on considerations and evaluations of reductions in tsunami event risks and the additional in-situ turning risk

Next, the evacuation of a ship having entered the Hamadera Passage was examined. As mentioned above, a ship proceeding through the passage cannot deviate from the passage. It is therefore assumed that the ship either returns to the entrance of the passage, or goes ahead until the end of the passage, turns around in the turning basin located in the eastern area of the passage, and then proceeds through the passage again in a westerly direction. To this procedure, an additional 30 minutes is required for leaving the berth.

The time required for evacuation into the open sea on the western side of the passage was examined by computer time domain simulation, with actual navigation situations acquired from the AIS data analysis considered in the analysis.

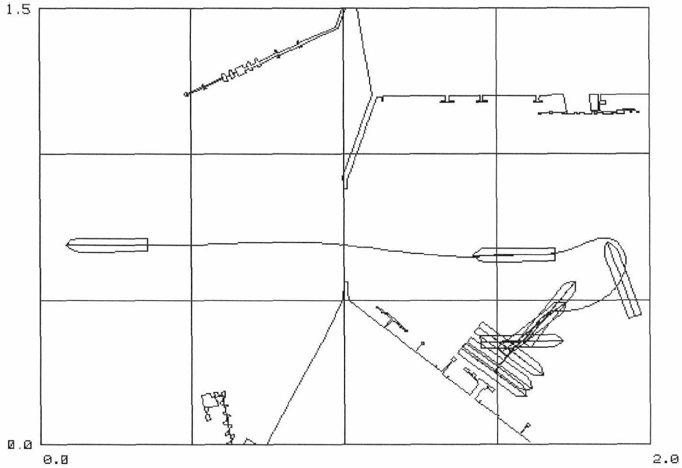


Fig. 8 Estimated evacuation locus during a tsunami event in the Sakai Senboku Port from an inbound mooring position (Case 1).

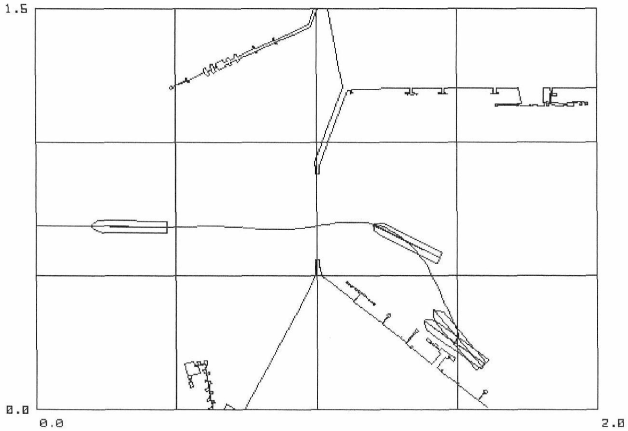


Fig. 9 Estimated evacuation locus during a tsunami event in the Sakai Senboku Port from an outbound mooring position (Case 2).

Moreover, anchoring computer simulations were carried out to confirm the safety under tsunami attack by use of a the three-dimensional lumped mass method that cables and an anchor are expressed as many springs and mass points. The anchoring position was set at 1.5 km western from the west end of the Hamadera Passage. The length of chains in this simulation was set as 4D +

145 m, where D: depth of the water. One of the results of calculation is shown in Fig. 10. The initial heading angle of this case was in the western direction. Although the ship was forced to move slowly by horizontal flow induced by tsunami, the anchor was not dredged when the flow is strongest.

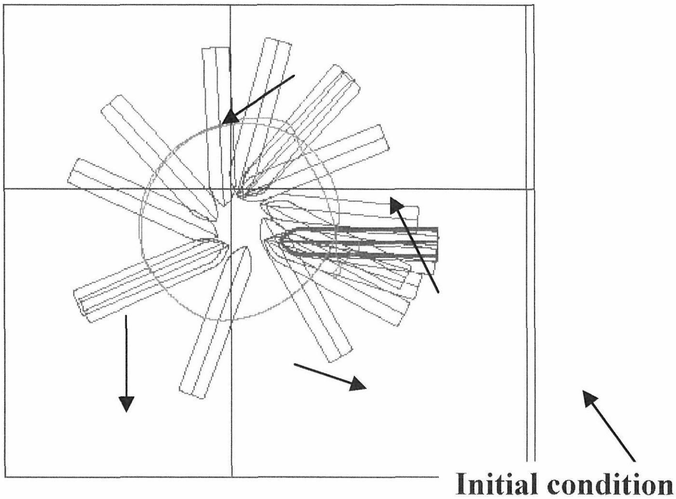


Fig.10 Ship locus under tsunami attack in anchoring condition

The results of the simulation are summarized as follows:

(1) During navigation: if the distance from the ship to the western end of the passage is less than 4,000 m.
The time required for evacuate the passage is less than 90 minutes.

(2) During navigation: the distance from the ship to the western end of the passage is greater than 4,000 m.
The time required for evacuate the passage is less than one hour and 30 minutes.

(3) During berth: Inbound direction.
The time required for evacuating the passage is less than one hour and 55 minutes.

(4) During berth: Outbound direction.
The time required for evacuate the passage is less than one hour and 30 minutes.
(Time required for recognizing the earthquake occurrence, 10 minutes; preparation for leaving, 30 minutes; unberthing procedures and moving to the entrance of the passage, 25 minutes; proceeding through the passage, 25 minutes)

(5) During anchoring:

The anchor was not dredged under horizontal current induced by the tsunami.

7 Conclusion

In this study, evacuation guidelines for an LNG ship, which is representative of a hazardous cargo carrier, were considered for the case of a ship entering the Sakai Senboku Port.

A ship in the Hamadera Passage can be successfully evacuated from the first tsunami event, such as one that has been estimated to arrive one hour and thirty minutes after the occurrence of the earthquake, by returning down the passage if the ship is less than 4000 m from the passage entrance. The ship can also be evacuated by going ahead, turning around and proceeding down the passage once more if the ship is already more than 4000 m down the passage.

It is possible that the ship may encounter the first tsunami event in the case where the ship begins to evacuate from an inbound mooring direction. However, in the case where the ship is moored in the outbound direction and is oriented toward the open ocean, it is likely to overcome the potential threat of the first tsunami event.

It is also possible to anchor in the appropriate evacuation area during a tsunami attack.

Acknowledgements

This work was partly supported by a Grant-in-Aid for Scientific Research (B) from the Japanese Ministry of Education, Sports, Culture, Science, and Technology (No. 19310122). The authors also wish to thank all the members of the maritime safety system laboratory at Kobe University for their assistance.

References

[1] Imamura, F(1996). "Review of Tsunami Simulation with a Finite Difference Method, Long-Wave Run-up Models", World Scientific, River Edge, World Scientific, River Edge, NJ, pp.43-87.

[2] The Japan Association of Marine Safety(1975). "The maneuvering guide for super large vessels", Seizando (in Japanese).

[3] Kobayashi, E., Shunichi, K., Kubo, M (2005). "A Basic Study on Ship Drifting by Tsunami", Journal of Kansai Zosen Kyoukai, Vol. 243, pp.49-55(in Japanese)

[4] Watanabe, H. (1985). "The compendium of tsunami disaster in Japan", Tokyo University Press(in Japanese) .

[5] The Headquarters for Earthquake Research Promotion, http://www.jishin.go.jp/main choukihyoka/ kaikou.htm(in Japanese).