Evacuation Assessment of a Large Passenger Vessel due to Tsunami Attack

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Kousuke Onoda**, Student Member, Rusmanto****, Member

Summary
Disaster mitigation management is considered a very important aspect in marine catastrophes, such as a tsunami, especially because drifting ships containing passengers and hazardous substances can cause a huge disaster in a port. It has already been analyzed that at the arrival of a tsunami, it is very hazardous for a large passenger vessel to evacuate passengers first. In this study, the assessment of evacuation at Osaka Bay in Japan is based on Automatic Identification System (AIS) data used as input for a Discrete Event Simulation (DES), which assesses ship evacuation time and using the Geographic Information System (GIS) to determine the locus of ships. The location of ship evacuation is decided in the anchorage area since the time needed for a ship to evacuate outside Osaka Bay is more than the predicted time of a tsunami arrival. In this paper, a preliminary proposed safe area for evacuation is evaluated and the possibility of large passenger vessel evacuation is shown.

1. Introduction
Earthquakes have continuously occurred along the Nankai trough located off the Kii Peninsula, Toukai area and Shikoku area of Japan for more than 1000 years. As of 1 January 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. The tsunamis that will be generated by these earthquakes will arrive at Osaka Bay within 1.5 hours after the earthquake occurrence. The tsunamis in Osaka Bay are characterized by the receding and approaching horizontal water flow associated with the sea surface slowly rising and falling. Before the arrival of the tsunami, ships are required to proceed outside the ports and to be anchored because ships inside the bay cannot be maneuvered due to the strong horizontal water movement. Moreover, these ships would be likely to drift and destroy many objects in Osaka Bay, thereby causing huge economic losses and endangering many living things, including humans. Some large passenger ships, which can carry approximately over 3500 people, should also evacuate immediately from the berth area to an appropriate safety area because a previous analysis has predicted that the evacuation time is not enough for passengers to embark from a large passenger vessel and evacuate to safe areas before a tsunami arrives.

Several studies on the evacuation of vessels in an emergency anchorage area have previously been carried out. Y oneda et al.2) evaluated the possibility of needed time for evacuation of vessels from several ports in Osaka Bay, such as Kobe Port, Osaka Port area, Sakai Senboku Port area and Hannan Port area to anchorage areas by using a deterministic assessment. However, this analysis is considered a macro assessment of evacuation since it does not consider each ship’s movement. Kobayashi et al.3) evaluated the possibility for a liquefied natural gas (LNG) vessel to evacuate to an emergency anchorage area considering two initial positions, e.g., outbound and inbound mooring positions of a vessel in Sakai Senboku Port, by using a simulation which is also considered a deterministic assessment. Their approach could be used for the investigation of vessel motions under the horizontal current induced by a tsunami while carrying out evacuation. In this paper, we discuss the main objective of the research, which is to evaluate whether there are possibilities for a large passenger vessel to evacuate from Tempozan Passenger Terminal in Osaka Bay, Japan to an emergency anchorage area in the case of tsunami arrival by using a Discrete Event Simulation (DES), which is considered the stochastic approach. This particular research objects such as a large passenger ship evacuation evaluation at Tempozan Passenger Terminal and the usage of DES for a large passenger vessel evacuation have not been carried in other studies.

In order to achieve this objective, several steps have to be taken into account. First is the framework of assessment, which includes the flow of the research as well as investigation of the Automatic Identification System (AIS) data, which describe the characteristics of ship velocity and movement through the Geographic Information System (GIS). Second, the tsunami arrival prediction, which shows velocity and elevation characteristics within time constraints is presented. In order to ensure that the emergency anchorage area is adequate, the ship maneuvering and motion induced by tsunami arrival are presented. Finally, a large passenger vessel evacuation simulation is carried out and evaluated by using a general discrete event simulation. The results of the ship evacuation assessments are evaluated with respect to the time of tsunami arrival in the bottleneck of the Osaka Port area, which is between Yumeshima and Sakishima and the emergency anchorage area, and whether there is a possible way for a large passenger vessel to evacuate to a safe area.
2. Framework of Assessments

The framework of a research as shown in Fig. 1 is started from the investigation of obtained AIS data by means of GIS at Osaka Bay area and a study area which is located at Tempozan Passenger Terminal. From this investigation, it is obtained any information relating to ships departure and arrival velocity, type and names of ships, ships locus and the needed time of ships to navigate from Tempozan Passenger Terminal to Tomogashima or Akashi Channel. Next, the location of anchorage area is evaluated in respect to a tsunami arrival time to be compared with the needed time of ships navigation from Tempozan Passenger Terminal to Tomogashima or Akashi Channel.

Moreover, it is considered that the tsunami arrival prediction, which is obtained from a mathematical model shown in Section 4, is used as the input of tsunami induced velocity components for ship motion in anchoring condition in the emergency anchorage area. The motion of an anchored ship is used to evaluate whether the emergency anchorage area is safe or not in the case of a tsunami disaster. Next step, the ship evacuation simulation is carried out.

The framework of the research work is shown in Fig. 1, which also shows that the determination of ship networking is carried out based on the AIS data of a ship’s location and speed in each time frame as well as the sea navigation chart of Osaka Bay. These data are input into the GIS to visualize the location of a ship in Osaka Bay. The AIS data provide ship information at specific times. The evacuation modeling is developed by the combination of GIS and DES. DES is one of the available tools to carry out dynamic system simulations.

Several authors have used GIS for evaluating transportation problems such as accidents and congestion, and especially to examine the geographical locations of these problems. Wiley et al.4) used the combination of DES and GIS for evaluating congestion management planning. Moreover, Erdogan et al.5) used GIS as a management system for accident analysis and determination of hot spots in Turkey. In this paper, GIS is used for determination of an emergency anchorage location for evacuation from a tsunami attack in Osaka Bay as well as development and determination of a ship network for evacuation. GIS is also used for the spatial evaluation of a ship’s arrival and departure from a port. The analysis results from the GIS and the AIS data, which are inputs for GIS are used for further assessment by DES.

Transportation simulations are generally divided into four classifications: submicroscopic, microscopic, mesoscopic and macroscopic simulation models6). The divisions of simulation models are based on the level of detail with which they represent the traffic system6). It is considered that DES is a mesoscopic simulation model6). DES represents a medium detail level with respect to the pertinent traffic entities and description level of these entities in relation to the flow model6). Moreover, it also specifies the behavior of the individual in probabilistic terms, which is a mesoscopic simulation characteristic6). Medium detail means that individual entities are difficult to be distinguished and traced. Moreover, the maneuvering of entities cannot be recognized and traced. In this case, DES is used to determine the needed time of ship for evacuation to an emergency anchorage area, because DES can be used for stochastic assessments depending on the availability of data, e.g., astern motions of vessels and speed deviations. However, it cannot be used for geographic assessments, such as the possibility of collisions. The results of the simulation are probabilistic instead of deterministic. There are several software applications which can be used for the DES model, such as GPSS, SIMSCRIPT, Arena, Simul8 and Micro Saint Sharp 2.5. The authors used Micro Saint Sharp 2.5 for the DES model. The integration of GIS, AIS and DES is the basis of this research. Then, the results of the ship evacuation simulation by using Micro Saint Sharp 2.5 is evaluated and compared with the tsunami arrival time prediction, which is obtained from a mathematical model shown in Section 4.
3. Investigation of Sea Traffic by AIS and GIS

3.1 Installation of AIS

The actual data of large passenger vessels are obtained from the AIS receiver installed at Kobe University, Fukae campus. Currently, AIS can recognize ships of more than 300 GT for international voyages and ships of more than 500 GT for domestic routes. Both static and dynamic ship data can be obtained. The dynamic information is updated every 2 to 10 seconds depending on the speed of a vessel.

The static information consists of the vessel’s maritime mobile service identity (MMSI), name of vessel, calling name, ship length, draft of ship, IMO number, ship breadth, type of ship and antenna position. The dynamic information consists of longitude, latitude, time, course, rate of return, speed over ground, navigation information, draft of ship, destination and type of cargo. Therefore, it is possible to record the time of a large passenger vessel’s departure and arrival at the Tempozan Passenger Terminal in Osaka Bay.

3.2 AIS data analysis and GIS

At Tempozan Passenger Terminal, shown in Fig. 2, there are 13 passenger ships which were recognized by the AIS from 8 August 2006 to 16 April 2007. Those ships visited the terminal at different times. The principal dimensions and arrival time are shown in Table 1. Moreover, in that time, AIS also recorded the largest cruise ship (ship C), which can accommodate a maximum of 4160 people, including passengers and crew.

At the recorded time, this ship had 1339 passengers’ and 650 crew’s cabins. In addition, Table 2 shows the time needed for navigation between Tomogashima or Akashi Channel and Tempozan Passenger Terminal.

As shown in Table 1, ship A through ship G data are used for analysis because they have similar characteristics, such as an initial astern motion as well as velocity data. Since the purpose of this assessment is to evaluate a large passenger ship departing and arriving at the Tempozan Passenger Terminal. The initial position of the ship was facing inward. Therefore, in order to evacuate from inside the port, the ship had to move astern, but it could not turn in a circle (turning back) since the vessel was so long. Moreover, she needed a spacious area to turn her hull and then move forward.

AIS was also recording the ship during departure and arrival. Fig. 3 shows that the ship first departed slowly and then the velocity of vessel rose gradually. When the vessel performed astern motion from the initial position alongside the berth, the velocity of the vessel rose gradually and then decreased. Before passing through the channel, the velocity of the vessel rose gradually and decreased when the pilot proceeded to get off board and rose again after the pilot got off board, as shown in Fig. 3. Fig. 4 shows that the velocity of the vessel was also decreasing when the ship approached the port channel, at the same time the pilot got on board, and the ship proceeded to the port. Moreover, from the AIS raw data, the time needed for each ship movement from one point to another one is calculated, as shown in Table 2. It is shown that time needed to pass through Tomogashima and A kashi Channel was roughly 2 hours 30 minutes.

3.3 Evacuation Assessment

The AIS receiver installed at Kobe University, Fukae campus. Currently, AIS can recognize ships of more than 300 GT for international voyages and ships of more than 500 GT for domestic routes. Both static and dynamic ship data can be obtained. The dynamic information is updated every 2 to 10 seconds depending on the speed of a vessel.

The static information consists of the vessel’s maritime mobile service identity (MMSI), name of vessel, calling name, ship length, draft of ship, IMO number, ship breadth, type of ship and antenna position. The dynamic information consists of longitude, latitude, time, course, rate of return, speed over ground, navigation information, draft of ship, destination and type of cargo. Therefore, it is possible to record the time of a large passenger vessel’s departure and arrival at the Tempozan Passenger Terminal in Osaka Bay.

Table 1 Principal dimensions and arrival time of vessels at Tempozan Passenger Terminal

<table>
<thead>
<tr>
<th>DATE</th>
<th>SHIPS</th>
<th>Length Overall (LOA) (m)</th>
<th>Breadth (B) (m)</th>
<th>Draft (d) (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>18/3/2007</td>
<td>A</td>
<td>270</td>
<td>32.2</td>
<td>7.9</td>
</tr>
<tr>
<td>7/3/2007</td>
<td>B</td>
<td>293.5</td>
<td>32</td>
<td>9.8</td>
</tr>
<tr>
<td>14/10/2006</td>
<td>C</td>
<td>290</td>
<td>37.5</td>
<td>8.05</td>
</tr>
<tr>
<td>10/03/2007</td>
<td>D</td>
<td>193</td>
<td>24.7</td>
<td>6.33</td>
</tr>
<tr>
<td>16/4/2007</td>
<td>E</td>
<td>238</td>
<td>30.2</td>
<td>7.6</td>
</tr>
<tr>
<td>08/11/2006</td>
<td>F</td>
<td>241</td>
<td>29.6</td>
<td>7.5</td>
</tr>
<tr>
<td>23/02/2007</td>
<td>G</td>
<td>162.3</td>
<td>21.34</td>
<td>7.9</td>
</tr>
<tr>
<td>20/10/2006</td>
<td>H</td>
<td>166.65</td>
<td>24</td>
<td>6.55</td>
</tr>
<tr>
<td>3/5/2007</td>
<td>I</td>
<td>219.5</td>
<td>30.78</td>
<td>-</td>
</tr>
<tr>
<td>06/10/2006</td>
<td>J</td>
<td>167</td>
<td>24</td>
<td>6.33</td>
</tr>
<tr>
<td>16/12/2006</td>
<td>K</td>
<td>183.4</td>
<td>25</td>
<td>6.5</td>
</tr>
<tr>
<td>8/8/2006</td>
<td>L</td>
<td>102.9</td>
<td>15.4</td>
<td>4.3</td>
</tr>
<tr>
<td>22/2/2007</td>
<td>M</td>
<td>154.6</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

Table 2 Time needed for navigation between Tomogashima or Akashi Channel and the Tempozan Passenger Terminal

<table>
<thead>
<tr>
<th>SHIPS</th>
<th>TIME</th>
<th>CHANNEL</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>2 hr 43 min</td>
<td>Tomogashima</td>
</tr>
<tr>
<td>B</td>
<td>2 hr 28 min</td>
<td>Tomogashima</td>
</tr>
<tr>
<td>C</td>
<td>2 hr 45 min</td>
<td>Tomogashima</td>
</tr>
<tr>
<td>D</td>
<td>2 hr 47 min</td>
<td>Akashi</td>
</tr>
<tr>
<td>E</td>
<td>2 hr 30 min</td>
<td>Tomogashima</td>
</tr>
<tr>
<td>F</td>
<td>2 hr 42 min</td>
<td>Tomogashima</td>
</tr>
<tr>
<td>G</td>
<td>2 hr 30 min</td>
<td>Tomogashima</td>
</tr>
<tr>
<td>H</td>
<td>2 hr 32 min</td>
<td>Tomogashima</td>
</tr>
<tr>
<td>I</td>
<td>2 hr 26 min</td>
<td>Tomogashima</td>
</tr>
<tr>
<td>J</td>
<td>2 hr 19 min</td>
<td>Akashi</td>
</tr>
<tr>
<td>K</td>
<td>2 hr 27 min</td>
<td>Akashi</td>
</tr>
<tr>
<td>L</td>
<td>1 hr 48 min</td>
<td>Akashi</td>
</tr>
<tr>
<td>M</td>
<td>2 hr 30 min</td>
<td>Akashi</td>
</tr>
</tbody>
</table>
Fig. 3 The large passenger ship's departure velocity and locus information

Fig. 4 The large passenger ship's arrival velocity and locus information
Evacuation Assessment of a Large Passenger Vessel due to Tsunami Attack

4. Mathematical Model of a Tsunami

The mathematical model of a tsunami\(^2,9,10\) is used for the prediction of tsunami arrival velocity and the elevation of the sea surface within time constrains in Osaka Bay. In addition, it is used for the limitation of evacuation time and input of the maneuvering of a cruise ship. The characteristics of the tsunami are expressed as follows for the coordinate system shown in Fig. 5:

\[
\begin{align*}
\frac{\partial \eta}{\partial t} + \frac{\partial M}{\partial x} + \frac{\partial N}{\partial y} &= 0 \\
\frac{\partial M}{\partial x} + g \frac{\partial^2 \eta}{\partial x^2} + \frac{\partial}{\partial t} \left( \frac{\partial M}{\partial y} + \frac{\partial N}{\partial x} \right) D &= 0 \\
\frac{\partial N}{\partial y} + g \frac{\partial^2 \eta}{\partial y^2} + \frac{\partial}{\partial t} \left( \frac{\partial M}{\partial x} + \frac{\partial N}{\partial y} \right) D &= 0
\end{align*}
\]

(1)

where,
- \(\eta\) : elevation from still sea water
- \(h\) : depth of still sea water
- \(t\) : time
- \(\rho\) : density of sea water
- \(x, y\) : coordinate system
- \(g\) : gravity acceleration
- \(D\) : depth of sea water (\(= h + \eta\))
- \(\tau_{x}, \tau_{y}\) : sea bottom friction in \(x, y\) direction
- \(M, N\) : \(x, y\) direction flow volume flux

5. Tsunami Simulation

The results of the tsunami arrival time prediction in several locations based on the mathematical model shown above are presented in this section. The time limitation was applicable for any ships in the Osaka Port area to evacuate from the port to the anchorage point. In this paper, it is assumed that the earthquake location is in Nankai trough according to an assumption provided by the Central Disaster Prevention Council, Japan as shown in Fig. 6, which would likely have a huge impact on the Osaka Bay area. The calculations are carried out based on 50 m mesh system. Moreover, the initial value of a tsunami calculation is based on fault model of earthquake as shown in Table 3 according to an assumption provided by the Central Disaster Prevention Council, Japan.

### Table 3 Fault Model of Earthquake

<table>
<thead>
<tr>
<th>Fault Location</th>
<th>Nankai Earthquake</th>
<th>Tonankai Earthquake</th>
</tr>
</thead>
<tbody>
<tr>
<td>Origin of Fault Plane</td>
<td>32.92° Latitude 135.60° Longitude</td>
<td>33.62° Latitude 137.23° Longitude</td>
</tr>
<tr>
<td>Fault Slip [m]</td>
<td>9.45</td>
<td>7.05</td>
</tr>
<tr>
<td>Fault Length [m]</td>
<td>150000</td>
<td>150000</td>
</tr>
<tr>
<td>Fault Width [m]</td>
<td>120000</td>
<td>70000</td>
</tr>
<tr>
<td>Fault Strike [Degree]</td>
<td>250</td>
<td>250</td>
</tr>
<tr>
<td>The Angle of Fault Inclination [Degree]</td>
<td>20</td>
<td>10</td>
</tr>
<tr>
<td>The Direction of Fault Slip [Degree]</td>
<td>117</td>
<td>127</td>
</tr>
<tr>
<td>The Depth of Fault Plane [m]</td>
<td>1000</td>
<td>1000</td>
</tr>
</tbody>
</table>

Tsunami arrival time estimation is determined at three locations, “A”, “B” and “C” points, which are located at 135.43° longitude, 34.66° latitude; 135.40° longitude, 34.64° latitude; 135.33° longitude, 34.60° latitude, respectively. The “A” point is the initial position of a large passenger ship, and is located in the berth. The “B” point is located in the neck of channel where the large passenger vessel passes. The “C” point is designated as the anchorage point for the large passenger vessel evacuation destination in the case of the tsunami since the location is considered near from an original berth and spacious enough for a ship maneuvering. Moreover, that location is considered as an anchorage area in the normal condition, therefore; it is deep enough for a ship to anchor in that designated location.

Fig. 7 represents the elevation of the sea surface and velocity at Tempozan Passenger Terminal denoted as point “A”. This figure shows that the first time of tsunami arrival is approximately 6800 sec and the first peak time of tsunami arrival is approximately 8130 sec. Elevation and velocity at the first peak time of tsunami arrival are approximately 1.5 meter and 0.55 m/s, respectively. In addition, when the highest velocity, which is approximately 1.5 m/s is occurred, elevation is approximately 0.46 m. If it is observed that the vessel may destruct the berth and endanger crew members or passengers on board as sea water is flowing and changing directions in a finite time during the tsunami arrival, then an immediate evacuation may have to be considered to avoid a huge disaster.

Fig. 8 shows the time histories of the elevation of the sea surface and velocity component at point “B”, which is considered a narrow area in the Osaka Port area and narrower than point “C”. The first time of tsunami arrival is approximately 6410 sec and the first peak time of tsunami arrival is approximately 7570 sec. Elevation and horizontal velocity in the first peak time of tsunami arrival is approximately 1.1 m and 2.1 m/s, respectively.

The time histories of the elevation of the sea surface and velocity components at anchorage point “C” are presented in Fig. 9. At point “C”, the first time of tsunami arrival is approximately 5470 sec. Moreover, the first peak time of tsunami arrival at point “C” is approximately 6880 sec and the horizontal velocity at “C” is 0.6 m/s. These explanations show the importance of tsunami arrival time and elevation.
and the horizontal velocity of each targeted area in order to evaluate the possibility for ships to evacuate to a sheltered area. Tsunami arrival time estimation has been evaluated at three locations, “A”, “B”, “C”, as shown in Fig. 10 and Table 4. Moreover, the results of the tsunami simulation are summarized in Table 4.

The results of the tsunami arrival simulation show that it is impossible for a ship to evacuate outside Osaka Bay, as the time needed for a vessel to proceed outside the bay is approximately 2 hr 30 minutes, as shown in Table 2. That evacuation time is more than the tsunami arrival time. Therefore, ships which are inside Osaka Bay should evacuate to the anchorage area, e.g., point C, shown in Fig. 10.

6. Ship Maneuvering Motions Prediction

The mathematical model of ship maneuvering motions is used for understanding the ship behaviors, e.g., the area of the large passenger ship motions due to the tsunami arrival in the anchorage area. By understanding these ship motions, it is possible to evaluate whether the vessel motion is safe enough.

6.1. Mathematical model of ship maneuvering motions

The motions of ship maneuvering are expressed as the following equations:

\[
\begin{align*}
(m + m_\psi) \dot{\psi} - (m + m_x + X_x) \psi = & \left( m + m_y + X_y \right) \psi + T_x \left( I_{zz} \psi - J_{zz} \right) \\
-\left( u_c \cos \psi - v_c \sin \psi \right) \left( m + m_y + X_y \right) \psi + & \left( v_c \cos \psi + u_c \sin \psi \right) \left( m + m_x + X_x \right) \psi + T_y \left( l_{zz} \right) \\
& N_x + P_{xT} + P_{yT} = \left( l_{zz} \right)
\end{align*}
\]

where,

\begin{itemize}
  \item \( \psi \): heading angle of a ship
  \item \( m \): mass of a ship
  \item \( m_x, m_y \): added mass of a ship in x,y directions
  \item \( I_{zz} \): mass moment of inertia of a ship about z axis
  \item \( J_{zz} \): added mass moment of inertia of a ship about z axis
  \item \( u, v \): velocity components in x,y direction
  \item \( u_c, v_c \): velocity components by tsunami in x,y direction
  \item \( r \): rate of turn
  \item \( X_x, Y_x, N_x \): longitudinal and lateral force and moment acting on a ship
  \item \( T_x, T_y \): tension force of anchor chain in x,y direction
  \item \( P_{xT}, P_{yT} \): length of force measured from ship center of gravity to the location of force in x,y direction
\end{itemize}

In addition, it is assumed that the working force and
moment of a ship hull which are induced by velocity components by a tsunami, \( u_c \) and \( v_c \), are expressed as the following equations:

\[
X_n = \frac{\rho}{2} \int L d\gamma \cdot C_{Dx} (\theta, \gamma) \quad (3) \\
Y_n = \frac{\rho}{2} \int L d\gamma \cdot C_{Dy} (\theta, H / d) \quad (4) \\
N_n = \frac{\rho}{2} \int L d\gamma \cdot C_{Dz} (\theta, H / d) + N_r (r, H / d)
\]

where,

- \( L, H, d \): ship length, depth of sea water and draft
- \( U_c, \theta_c \): relative flow velocity and direction
- \( \rho \): density of sea water
- \( C_{Dx}, C_{Dy}, C_{Dz} \): drag coefficient in \( x \), \( y \) direction and drag coefficient of moment

### 6.2. Evaluation of ship motions in anchoring condition

It is assumed that the ship is in anchoring condition since ship masters usually feel that it is safer to anchor a ship in the case of a worse condition such as a bad weather than to maneuver in heaving to, because it is possible to anchor in most coastal area in Osaka Bay and to prevent a ship from uncontrolled vessel movements causing more spanned area of ship motions.

The ship motions are generated by using a computer simulation which comes from equations (2) and (3). The simulation is used to determine whether the representative point is considered a safe area.

Simulation of an anchored ship motions under tsunami attack is performed. Longitudinal, lateral and moment acting on ship due to horizontal velocity of a tsunami arrival cause tension force of chains. The calculation of force acting on an anchor and anchor chains are assumed as shown in equation (4) and Fig. 11. The vessel representing the large passenger ships is ship \( C \) since it is considered the largest. It is assumed that before the tsunami arrival, the position of the anchored ship is at the anchorage point \( C \), as shown in Fig. 10.

The calculation is based on a single anchoring simulation as a basic study. The simulation is carried out by "Lumped Mass Method" as shown in Fig. 11 and equation (4). The "Lumped Mass Method" expresses a cable and an anchor as many mass points and springs. The equations of motion for each mass point are solved and their motions and tensions are obtained.

\[
\begin{align*}
F_{xj} &= T_j \sin \alpha_j - T_{j-1} \sin \alpha_{j-1} + F_{axj} + F_{gxj} \\
F_{yj} &= T_j \sin \beta_j - T_{j-1} \sin \beta_{j-1} + F_{ayj} + F_{gyj} \\
F_{zj} &= T_j \sin \gamma_j - T_{j-1} \sin \gamma_{j-1} + F_{azj} + F_{gzj}
\end{align*}
\]

where,

- \( F_{xj}, F_{yj}, F_{zj} \): force of mass point in \( x, y \) and \( z \) direction at point \( j \)
- \( F_{axj}, F_{ayj}, F_{azj} \): drag force of chain in \( x, y \) and \( z \) direction at point \( j \)
- \( F_{gxj}, F_{gyj} \): friction force between chain and sea bed in \( x \) and \( y \) direction at point \( j \)
- \( T \): tension force of mass point

#### Table 5 Input simulation assumptions

<table>
<thead>
<tr>
<th>Holding power</th>
<th>150.5 tons</th>
</tr>
</thead>
<tbody>
<tr>
<td>Anchor type</td>
<td>Stockless</td>
</tr>
<tr>
<td>Length of chain</td>
<td>209 m</td>
</tr>
<tr>
<td>Diameter of chain</td>
<td>127 mm</td>
</tr>
<tr>
<td>Weight of anchor</td>
<td>21.5 ton</td>
</tr>
<tr>
<td>Type of sea bed</td>
<td>Sand</td>
</tr>
<tr>
<td>Holding power coefficient</td>
<td>7</td>
</tr>
<tr>
<td>Coefficient of chain</td>
<td>2</td>
</tr>
<tr>
<td>Depth of sea water</td>
<td>16 m</td>
</tr>
</tbody>
</table>

To conduct the ship movement simulation, there are several assumptions which have to be considered, as shown in Table 5. From the computer simulation, the maximum distance movement of the large passenger vessel is approximately a radius of 0.5 km. The result of the simulation is shown in Fig. 12, which depicts the movement of the anchored large passenger vessel every 100 sec. It also shows that the vessel may be safe enough when a tsunami comes because the anchor is not dredged under the horizontal current induced by the tsunami. This means that the holding power of the anchor is strong enough to prevent drifting of the vessel.

Moreover, to minimize collisions between vessels during anchoring, there should be some inter-distance between vessels in the anchorage area when the vessels proceed to that area. The determination of the inter-distance is based on the prediction of the ship movement in the anchored condition, as shown in Fig. 12. If the area of evacuation is approximately 1 km in diameter, it is considered a safe condition for other vessels. Therefore, it is proposed that all ships should keep a distance of approximately 1 km between vessels, as shown as the black circles in Fig. 13. In other words, other vessels which are similar in size to ship \( C \) also should have an evacuation area point approximately 1 km in diameter. It is reasonable that other drifted ships may not have spanned areas as same as this type of ship in the case of a tsunami arrival. However, by considering a safety point of view and a preliminary evaluation, any ships which have size less than about 290 m have to keep a distance approximately 1 km since the spanned area of ships having length less than 290 m would be less than 1 km in diameter.
7. Ship Evacuation Simulation

After ensuring that the location of the emergency anchorage area is safe enough, the next step is to evaluate the large passenger ship evacuation time by using DES. From this calculation, it can be shown if the ship could be evacuated to the anchorage area before arrival of the tsunami.

7.1 Calculation assumptions

The ship evacuation simulation is based on DES, which can develop a model with the assumption that the state variable changes instantaneously at separate points of time\(^ \text{12} \)\(^ \). DES also considers an individual entity as more important than the aggregate of entities. This means that each passenger ship is assumed to be altered instantaneously at a specific time. Moreover, the simulations do not assume that each entity is a group of movements, since individual movements are most important\(^ \text{12} \).

In a comparison of DES with analytical approaches, DES has stochastic and uncertainty characteristics. In contrast, analytical approaches have deterministic and certainty characteristics, which mean the result of the assessment has an exact value.

In this calculation, the initial position of the ship is located at Tempozan Passenger Terminal since the position of the vessel which is in a berth is more dangerous than a position outside the Osaka port area. The calculation of total time needed for evacuation generally is expressed as follows:

\[
T_{\text{total}} = t_1 + t_2 + t_3
\]

where,

\[
\begin{align*}
T_{\text{total}} &: \text{total time needed for the vessel in all clusters} \\
t_1 &: \text{response time of the crew to realize the existence of disaster} \\
t_2 &: \text{time for a ship to reach her destination} \\
t_3 &: \text{time needed for a ship for anchoring process} \\
T_i &: \text{time needed for each vessel in cluster } i \\
dS_i &: \text{distance spent by each vessel in each cluster } i \\
V_i &: \text{average speed in cluster } i, \text{ which is obtained from AIS data, and then generated by using a pseudo-random number generator}
\end{align*}
\]

For example, for the calculation of the validity of the simulation, the clusters of data are based on Fig. 18 and Table 7. Those show that there are the following six clusters: Leaving port \((T_1)\), Departure 1 \((T_2)\), Departure 2 \((T_3)\), Departure 3 \((T_4)\), Passing Channel \((T_5)\) and End Arrival \((T_6)\) which are represented by point A to 1, 1 to 2, 2 to 3, 3 to 4, 4 to 5A and 5A to 6A respectively as shown in Fig. 14. Therefore, in mathematical form this is expressed as follows:

\[
t_2 = \sum_{i=1}^{6} T_i \tag{6}
\]

Moreover, to calculate the time needed to reach the anchorage point, there are 10 (ten) clusters of data, shown in Table 6, Table 7 and Fig. 19: Leaving port \((T_7)\), Departure 1 \((T_8)\), Departure 2 \((T_9)\), Departure 3 \((T_{10})\), Arrival 1 \((T_{11})\), Arrival 2 \((T_{12})\), Arrival 3 \((T_{13})\), Arrival 4 \((T_{14})\), Arrival 5 \((T_{15})\) and Arrival 6 \((T_{16})\) which are represented by point A to 1, 1 to 2, 2 to 3, 3 to 4, 4 to 5 and 5 to 6 respectively as shown in Fig. 14. Moreover, distance between point 6 and C as shown in Fig.14 is divided by 4 clusters as follows: Arrival 3 \((T_{17})\), Arrival 4 \((T_{18})\), Arrival 5 \((T_{19})\) and Arrival 6 \((T_{20})\). Therefore, in mathematical form, the calculation is expressed as follows:

\[
t_2 = \sum_{i=1}^{10} T_i \tag{7}
\]

The response time of the crew, in the case of a disaster, and the anchoring time of a ship are not considered in
probably distribution form since there are not available appropriate data to make such a calculation. The response time consists of the needed time of crew to realize that there is a tsunami and the needed time of crew to make preparation to proceed to the anchorage area considered from detaching the mooring ropes. However, in this case, when the tsunami arrives, it is assumed that the ships are ready to proceed to anchorage area since a cruise just arrives at a berth. The pilot is still on board, the engines are still running and she is not in moored condition. Then, a ship master decides to leave a berth immediately. Therefore, it is assumed that the response time of crew is approximately 10 minutes\textsuperscript{10}.

When the ship arrives at emergency anchorage point (point C), the anchoring time of a ship ($t_3$) is assumed approximately 10 minutes based on ship officer’s opinions by interview. The anchoring time of a ship consists of preparation time for launching the anchor and the releasing of the anchor as the normal condition of anchoring process. The input time data are based on a probability distribution of each cluster. For example, the time of leaving follows a lognormal distribution, as shown in Table 6. The arrival times of passenger ships are randomly generated and the uncertainty of the evacuation time of each passenger is modeled by a probability distribution having a range of values. Then, the simulation is conducted several times and compared to time data from the AIS receiver to learn the degree of evacuation simulation validity.

7.2 Clusters of data

Before carrying out the probability distribution assessment, we apply clustering data to obtain the appropriate simulation results. Cluster models are characterized by the central role of the clusters of ships. A cluster is a group of ships that share specific properties\textsuperscript{6}. In this case, the clustering is conducted based on the velocity difference data of a vessel as well as the time difference data of vessels which are obtained by the AIS receiver.

The velocity different data are based on the velocity of a large passenger ship (Ship C). The needed time data are obtained from several large passenger vessels when those ships perform astern motion from the port to a more spacious area for turning their hull. Those data are used because they have uncertainty due to several possible astern motions, as shown in Fig. 15.

In addition, the data for the prediction of a ship evacuation are obtained from the combination of arrival and departure velocities of each ship. Then, those data are clustered based on the velocity characteristics of the ship movement. Figs. 16 and 17 show that the ship velocities are similar when the velocity of the ships is increasing and decreasing. From this standpoint, the movements of ships are divided by several clusters which have constant acceleration and can be merged, and the time data can be analyzed statistically to learn the type of probability data distribution.

Regarding these assumptions, Leaving port, Departure 1, Departure 2 and Departure 3 cluster data, shown in Table 6 and Table 7, are taken from the needed time and ship C velocity data, respectively, which are represented as A1-A2 in Fig. 16. Moreover, the arrival movement data, which are from the bottleneck of the Osaka Port area at point B to the anchorage point at point C, as shown in Figs. 10 and 13, are obtained from velocity data represented as D1–D2 in Fig. 17 when the ship C velocity is gradually decreased.

![Fig. 15 Initial movement of vessels, as visualized by GIS](image)
7.3 Assumptions of input probability distribution

Statistical analysis is an important technique to determine and select input probability distributions before carrying out the DES of a large passenger vessel. Each cluster data is then analyzed using the Kolmogorov-Smirnov (K-S) test by means of a goodness of fit test software named EasyFit to ensure that each data follows one of some specific probability distributions.

Table 6 Input probability distribution (time data)

<table>
<thead>
<tr>
<th>No</th>
<th>Types of cluster</th>
<th>Distribution type</th>
<th>Parameter μ: mean; σ: standard deviation (sec)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Leaving Port</td>
<td>Lognormal</td>
<td>µ:642.11 σ:97.76</td>
</tr>
<tr>
<td>2</td>
<td>Departure 1</td>
<td>Lognormal</td>
<td>µ:194.72 σ:67.50</td>
</tr>
<tr>
<td>3</td>
<td>Departure 2</td>
<td>Lognormal</td>
<td>µ:313.37 σ:69.15</td>
</tr>
<tr>
<td>4</td>
<td>Departure 3</td>
<td>Lognormal</td>
<td>µ:484.32 σ:94.67</td>
</tr>
</tbody>
</table>

Table 7 Input probability distribution (velocity data)

<table>
<thead>
<tr>
<th>No</th>
<th>Type of cluster</th>
<th>Distribution type</th>
<th>Parameter μ: mean; σ: standard deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Leaving Port</td>
<td>Lognormal</td>
<td>µ:412.82 σ:6.40</td>
</tr>
<tr>
<td>2</td>
<td>Departure 1</td>
<td>Lognormal</td>
<td>µ:181.62 σ:2.57</td>
</tr>
<tr>
<td>3</td>
<td>Departure 2</td>
<td>Lognormal</td>
<td>µ:264.55 σ:7.84</td>
</tr>
<tr>
<td>4</td>
<td>Departure 3</td>
<td>Lognormal</td>
<td>µ:466.02 σ:31.85</td>
</tr>
<tr>
<td>5</td>
<td>Arrival 1</td>
<td>Lognormal</td>
<td>µ:1265.70 σ:3.90</td>
</tr>
<tr>
<td>6</td>
<td>Arrival 2</td>
<td>Lognormal</td>
<td>µ:171.62 σ:0.76</td>
</tr>
<tr>
<td>7</td>
<td>Arrival 3</td>
<td>Lognormal</td>
<td>µ:200.44 σ:1.16</td>
</tr>
<tr>
<td>8</td>
<td>Arrival 4</td>
<td>Lognormal</td>
<td>µ:108.81 σ:0.16</td>
</tr>
<tr>
<td>9</td>
<td>Arrival 5</td>
<td>Lognormal</td>
<td>µ:83.13 σ:6.04</td>
</tr>
<tr>
<td>10</td>
<td>Arrival 6</td>
<td>Lognormal</td>
<td>µ:48.73 σ:2.63</td>
</tr>
<tr>
<td>11</td>
<td>Passing Channel</td>
<td>Normal</td>
<td>µ:685.40 σ:9.13</td>
</tr>
<tr>
<td>12</td>
<td>End Arrival</td>
<td>Normal</td>
<td>µ:1195 σ:22.50</td>
</tr>
</tbody>
</table>

The data results are used as input in equation (5) to attain the evacuation simulation result. These clustered data based on the velocity data are slightly diverse in comparison to the time data since the characteristics of the ship velocity data are different.

The mean (μ) of each cluster means the average time of each vessel to spend time in cluster i. The standard deviation (SD) represents the dispersion of obtained time data.

Table 6 shows the results of the goodness of fit test using the K-S test. The results are based on the needed time data of all vessels which were performing astern motions, as shown in Fig. 15. As shown in Table 6, the majority of probability distribution data is lognormal. The only different values are the mean and standard deviation of each cluster of data.

Moreover, Table 7 shows the results of K-S test conducted and analyzed for the velocity data of ship C after conversion to time data. To obtain time data from ship C, the velocity data is first analyzed by using the K-S test to acquire velocity probability distribution data. Next, random data is generated by using the selected probability distribution. Several average velocities of a ship are obtained, and by using equation (5), the time needed of each cluster is acquired. Then, several time data of a ship in each cluster are analyzed by the K-S test by means of the EasyFit to obtain the input probability distribution of each cluster of time data.

The mean (μ) of each cluster means the average time of each vessel to spend time in cluster i. The standard deviation (SD) represents the dispersion of obtained time data.

7.4 Assumptions of evacuation modeling

As already explained, an evacuation simulation is conducted by using DES. To ensure the appropriateness and validity of DES, a modeling simulation is developed, as described in Fig. 18, which shows the modeling simulation of a large passenger vessel from the port to the location near the anchorage point or point 6A which is located at 135.33° longitude and 34.61° latitude as shown in Fig. 14. Another simulation, shown in Fig. 19, is the modeling of a large passenger ship proceeding to the anchorage area; the evacuation route of the ship can be seen in Figs. 10 and 13. A vessel spends time in each cluster in the model, for example, leaving port, departure 1. Probability distributions which have been analyzed are used as input of each cluster, as shown in Figs. 18 and 19. During the simulation, each cluster generates data randomly based on the type of probability distribution.
is between 52 min 56.80 sec and 53 min 3.20 sec. Moreover, is 53 min ± 3.20 sec. In other words, the average arrival time confidence level is 95% for the normal distribution, the average of the ship movement (scenario A) is shown in Table 9. This table shows that the result of the average arrival time of the ship to the anchorage point is approximately 35.47 sec. In addition, if it is assumed that the confidence level is 95% for the normal distribution, the result of this simulation is shown in Fig. 22, which shows that the evacuation time is approximately 3243 to 3847 sec with confidence level 95% for the normal distribution. The result of the simulation which considers several initial movements of vessels (scenario B) is shown in Table 10. This table shows that the average of simulation time for a vessel to proceed to an emergency anchorage area is approximately 58.8 min and SD is about 159 sec. Moreover, if it is assumed that the confidence level is 95% for the normal distribution, the prediction of the average arrival time is about 58.8 min ± 13 sec. In other words, the average arrival time is between 58 min 35 sec and 59 min 1.2 sec. In addition, the result of this simulation is shown in Fig. 22, which shows that the evacuation time is approximately 3243 to 3847 sec with confidence level 95% for the normal distribution.

### 7.5 Results of evacuation simulation

The results of the simulation validity investigation using DES are summarized in Table 8. The validity of the simulation is examined by comparing the simulation results and real time movement data. Real time movement data are obtained from the AIS data of ship C proceeding from the port to the desired point. The average time result of the simulation is about 3206 sec which is considered less than the real time movement data and the standard deviation (SD) is about 44.48 sec, as shown in Table 8. The error result is approximately 15 sec. However, if it is assumed that the confidence level is 95% meaning that the interval data which are used are between 0.025 and 0.975 for normal distribution, the results of the simulation are approximately 3123 to 3293 sec, as shown in Fig. 20. This means that the real time needed lies between these values. Therefore, DES seems appropriate to conduct simulation assessments.

The result of the simulation which considers one type of ship movement (scenario A) is shown in Table 9. This table shows that the result of the average arrival time of the ship to the anchorage point is approximately 53 minutes and SD is about 35.47 sec. In addition, if it is assumed that the confidence level is 95% for the normal distribution, the prediction of the average arrival time to the anchorage point is between 52 min 56.80 sec and 53 min 3.20 sec. Moreover, if it is assumed that confidence level is 95% for the normal distribution, the evacuation time is approximately 3138 sec to 3274 sec, as shown Fig. 21.

The result of the simulation which considers several initial movements of vessels (scenario B) is shown in Table 10. This table shows that the average of simulation time for a vessel to proceed to an emergency anchorage area is approximately 58.8 min and SD is about 159 sec. Moreover, if it is assumed that the confidence level is 95% for the normal distribution, the prediction of the average arrival time is about 58.8 min ± 13 sec. In other words, the average arrival time is between 58 min 35 sec and 59 min 1.2 sec. In addition, the result of this simulation is shown in Fig. 22, which shows that the evacuation time is approximately 3243 to 3847 sec with confidence level 95% for the normal distribution.
remaining time for preparation of leaving and anchoring. Average result of simulation, which is the most possibility simulation time respectively. However, by considering maximum time of evacuation and average minimum of between 27 minutes and 38 minutes by considering anchoring the ship at an anchorage area are approximately Yumeshima and Sakishima, as well as the last evacuation Figs. 10 and 13 of the Osaka Port area, which is between As shown in Table 11, a vessel can possibly avoid the first speed of the vessel decreases. shown Figs. 10 and 13 of the Osaka Port area and after the ship passes the bottleneck channel at point B, as shown Figs. 10, 13 of the Osaka Port area and after the speed of the vessel decreases.

The results of the simulations are summarized as follows. As shown in Table 11, a vessel can possibly avoid the first tsunami arrival in the bottleneck at point B, as shown in Figs.10 and 13 of the Osaka Port area, which is between Yumeshima and Sakishima, as well as the last evacuation destination at point C, as shown in Figs. 10, 13 and 14. The total remaining time for response time of crews and anchoring the ship at an anchorage area are approximately between 27 minutes and 38 minutes by considering maximum time of evacuation and average minimum of simulation time respectively. However, by considering average result of simulation, which is the most possibility remaining time for preparation of leaving and anchoring process, it seems that the remaining time is between 32 minutes and 38 minutes. Therefore, crews should conduct immediate action and preparation to minimize the preparation of leaving and anchoring process time in the case of a moored ship condition. As a result, a tsunami prevention drill could be required to minimize time of a ship evacuation.

Moreover, if it is assumed that the ship is ready to leave as well as the amount of the response time of the crew and the needed time of an anchored ship are assumed approximately 20 minutes, the vessel will spend a maximum of approximately 84 minutes or 1 hr 24 minutes in scenario B to evacuate toward the anchorage area. This time is shorter than the first time of tsunami arrival. Therefore, initially, when the passenger ship arrives at point C (anchorage point), as shown in Figs. 10, 13 and 14, this vessel is not facing the first time of tsunami arrival. In other words, it is possible for the large passenger ship to evacuate from Tempozan Passenger Terminal to the emergency anchorage area.

### 8. Conclusion and Future Work

From the ship motion assessment at the tsunami arrival, it seems that the vessel motion diameter is approximately 1 km. Therefore, each vessel should keep the distance between vessels at approximately 1 km. Furthermore, the preliminary proposed anchorage area for evacuation is about 1 km in diameter.

By using the Discrete Event Simulation (DES), the result of simulation of the evacuation time is estimated as shorter than that calculated from real time ship movement data. Nevertheless, the result of the simulation is close to the real time data. Therefore, it is believed that the DES is sufficient for use in evacuation simulations if the data are appropriate. The DES is also sufficient to evaluate the ship evacuation time by considering movements of several vessels which are represented by a probabilistic distribution. However, DES cannot evaluate the collision possibility since it is not possible to perform a graphical simulation assessment and it is difficult to trace and distinguish each entity. DES also cannot evaluate the effect of the tsunami force to the ship. Therefore, it is not recommended to use DES for those types of evaluations.

By using DES, it is predicted that the average arrival time of the ship from the port to an anchorage point is considered a safe area during tsunami arrival is approximately 53 minutes and 58.80 minutes for an initial movement of a ship and several initial movements of ships leaving the port, respectively. Moreover, by considering the initial astern motions of the ship, confidence level 0.95, crew response time and the anchored ship time, the maximum time of the ship evacuation is approximately 84 minutes. That time is considered shorter than the first tsunami arrival time at the anchorage point. Therefore, it is possible for the large passenger vessel to proceed to a safe area in the case of tsunami arrival.

The good preparedness of crews, facing a tsunami arrival could minimize the ship evacuation time which is contributed by anchoring process and leaving process due to the availability of the limitation remaining time, which is approximately between 32 minutes and 38 minutes.
The impact of traffic density inside Osaka Port area has not yet been considered. More vessels may cause a longer evacuation time for a large passenger vessel and an increased probability of a collision among vessels. Therefore, this condition has to be taken into account since a traffic accident in the narrow channel of Osaka Port area could be very dangerous. Moreover, the ship motion evaluation is only based on a large passenger vessel without considering other vessels. Future research includes an investigation of the effect of traffic density for ship evacuations inside Osaka Port area as well as an investigation of several sizes of ships motion due to a tsunami attack.

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