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Detection of Three-Dimensional Center of Gravity for ship capsizing prevention requiring no knowledge of ship parameters or loading conditions

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ABSTRACT
Ships have become an indispensable transportation method in global logistics because of their capabilities for transporting huge cargoes at low cost. Maritime transportation safety issues are important research objectives for the support of sustainable logistics. Capsizing accidents often cause devastating losses to logistics and supply chain stakeholders, and severely damage marine environments. This article presents a new method able to prevent capsizing accidents without any ship information or parameters, or conditions under which the ship is loaded. This article presents a means of calculating wave height based only on the ship's motion, which can in turn affect the ship's motion, even causing a capsizing accident.
Keywords: *Ship accident, Capsizingprevention, D3DCG, Wave height.*

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I. INTRODUCTION

For global logistics, many transportation methods exist. Whether for short distance or long-distance transportation, ships have become an indispensable transportation method in global logistics because of their capabilities for transporting huge cargoesat low cost. However, once a ship experiences an accident at sea, it can lead to catastrophic damage to life, property, and infrastructure, and to severe damage to marine environments(Toffoli et al., 2006). Therefore, maritime transportation safety issues are important research objectives to support sustainable logistics. Capsizing accidents often cause devastating losses to stakeholders in logistics and supply chains, and severe damage to the marine habitats.

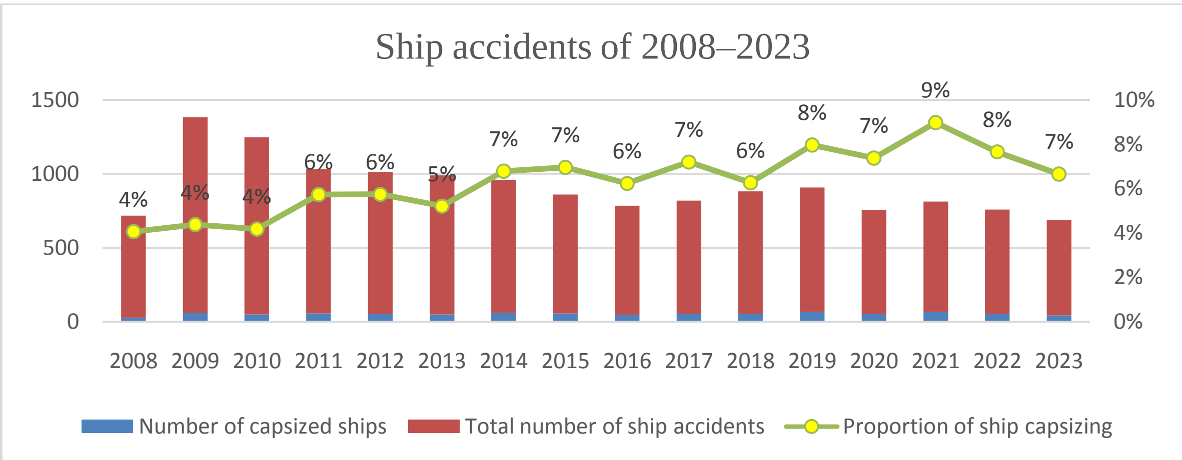

Figure 1 Total number of ship accidents and proportionsof capsized ships

According to historical and recent data, along with the development of global trade, over 600 complex-type ship accidents occur every year. From 2008 through 2023, many ship accidents have occurred worldwide, with ship capsizingaccidents accounting for a large share every year (MLITT JTSB, 2024). Especially after 2011, although the total numbers of ship accidents have decreased, the proportions of ship capsizing accidents have exceeded 5%. Ship capsizing accidents have always maintained an upward trend. Although the trend has declined since 2021, the proportion among all ship accidents is high.Ship capsizing accidents have occurred more than 45 times annually since 2010, accounting for no less than 4% of all ship accidents (Figure 1). Given this background, this article describes development of a new method able to prevent capsizing accidents without any ship information or parameters or the conditions under which the ship is loaded. Evaluating ship capsizing accidents often requires an understanding of a series of ship parameters and load condition (Kim et al., 2015). The prediction of ship capsizing is often a complex process. In earlier studies, the ship motion state has been observed based on time changes (Phoo and Watanabe, 2017). This article presents a method for calculation of the risk of ship capsizing by controlling variables.

II. MATERIAL AND METHODS

These analyses use a ship scale model and an air pump as a wave generator to simulate the trend of a ship on a water surface affected by waves. Weights of 1 kg and 0.106 kg are used to simulate the weight of cargo loaded on the ship. The ship motion data are received by a motion sensor that can record the angle, angular velocity and acceleration from three directions. This motion sensor's sampling rate is 20 Hz. The ship center of gravity height (Song, 2020) is detected using Detection of Three-Dimensional Center of Gravity (D3DCG; Watanabe, 2017) to calculate the risk of capsizing. Experiments were conducted while changing the loading weight and loading height of the ship scale model when the information and parameters of the ship are unknown.

2.1DetectionofThree-Dimensional CenterofGravity (D3DCG)

D3DCG is a method of determining the center of gravity position based on the motion state of an object. D3DCG is derived from ship buoyancy principle. On a calm water surface, the ship maintains vibration on the water surface. The frequency of vibration depends on the distance from the motion axis to the center of gravity. D3DCG can estimate the center of gravity by estimating the resilience. Ships always have these six kinds of motion in the water surface including heave, roll, surge, pitch, sway and yaw. Particularly, the heaving motion and rolling motion are necessary for D3DCG. The ship movement state is portrayed in Figure 2 by a cross-sectional view from the bow to stern direction. Waves appearing on the water surface are generated by circular motion, which diminishes and eventually reaches zero as the distance from the surface increases. This stable point can be considered the fulcrum of the wave motion described previously. In other words, it is the wave motion axis. According to the new concept of the D3DCG, this axis also involves hull oscillation and affects the stability of the ship to a considerable degree. Results show that the rolling of the ship is accompanied by the wave. The right to left swing width becomes larger with the wave height.

According to the presented above, the D3DCG equation is that shown below.

$$l^2 + \frac{g}{4\pi^2 v^2} l - \frac{b^2 v'^2}{4v^2} = 0\#(1)$$

$$l_{max} = \frac{\pi^2 v'^2 b^2}{g}\#(2)$$

$$\cos\theta_{max} = \frac{l}{l_{max}}\#(3)$$

Equations (1), (2) and (3) are combined to obtain equation (4).

$$\frac{16\pi^4 v^4}{g^2} l^3 + \frac{8\pi^2 v^2}{g} l^2 - \frac{v^2}{v'^2} l - \frac{g}{4\pi^2 v'^2} = 0\#(4)$$

$$h_{max} = \frac{2b}{\pi}\sin\theta_{max}\#(5)$$

Here, $v$represents the horizontal vibration (rolling) frequency, v' denotes the vertical vibration (heaving) frequency, l stands for denotes the distance between center of gravity and the axis, and l_{max} expresses the maximum height of l to be stabilized. In the equations, θdenotes the inclination angle of the center of gravity, θ_{max} represents the maximum stable inclination angle of the center of gravity, π represents the ratio of the circumference of a circle to its diameter, g represents a gravitational acceleration, and $b$denotes horizontal width which produces the restoring force.

D3DCG can evaluate the center of gravity by estimating the restoring force. According to Figure 3, the distance of horizontal vibration is b, when the ship's horizontal motion exceeds b, the ship will capsize. Also,θ_{max}denotes the maximum angle of l to be stabilized.Additionally, from the perspective of the natural center of motion, if the ship tilts on the water surface, then the value ofl_{max}decreases as the value of $b/2$increases, as shown in Figure 6. At a certain point, the values of l_{max} and l become equal. Furthermore, if l_{max} becomes less than l, then this corresponds to the condition for capsizing: the ship will capsize. The value $b/2$ is obtainable using a simple mathematical equation as presented above. In this case, the rolling motion is akin to a simple pendulum motion. The heaving motion is a simple harmonic motion, which has a straightforward comparison in physics.

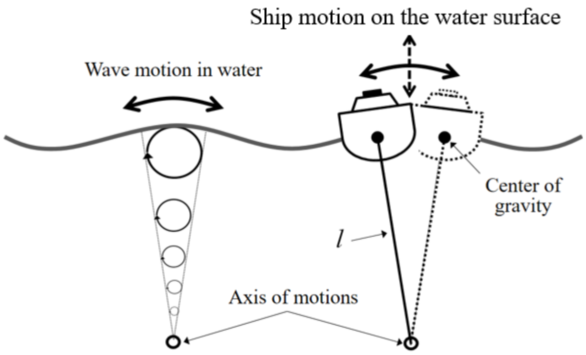

Figure 2 Movement of ships on water surface

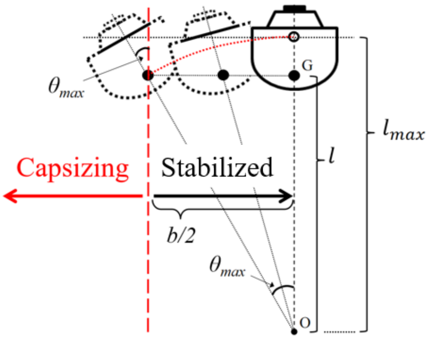

Figure 3 Ship stability and capsizing conditions

2.2Loading weight experiment

The author used weights of 1 kg and 0.106 kg to simulate the weight of the ship's load, used an air pump as a wave generator to create continuous and stable waves, simulated the ship motion on the water surface, and collected data of the ship's motion on the water surface using a motion sensor. Starting from the ship being unloaded, gradually add weights to the shelf of the ship scale model, observe the ship's motion status, and calculate the ship's motion frequency through fast Fourier Transform (FFT) to calculate data related to the risk of capsizing, such as the height of the ship's center of gravity.

Figure 4 Ship scale model and motion sensor position

The author placed the motion sensor in the center of the ship scale model. To ensure that the height remains unchanged when increasing the load, the author used a long board to load the weights as shown in Figure 4. As presented in Figure 5, starting from the ship scale model with no load, gradually place weights on the shelf of the ship scale model to increase the loading weight of the ship from 0 kg to 1.636 kg. The sum of the weights increased from 0 kg to 0.212 kg.Little change occurred in the motion state of the ship scale model. Therefore, the author replaced the weights directly with a 1 kg weight and continued to observe the motion state of the ship scale model. As the weight increased from 1 kg to 1.424 kg, the ship movement trend changed very little.

Figure5 Loads of 0 kg –1.636kg

Capsizing occurred when the load increased to 1.636 kg. This process occurs very slowly. The ship tilts bit by bit until it exceeds the maximum capsizing angle. In this case, the weights do not shift because of the rolling of the ship. If the weights shift with the rolling of the ship, the capsizing speed of the ship will be faster. During these load experiments, as the loading weight of the ship increases, the ship draft depth also changes. However, the width and the deflection state of the ship's sway were not determined. Therefore, continuous experiments must be conducted for research.

The motion sensor recorded the time domain data of ship scale model motion, after Fast Fourier Transform (FFT), the time domain data became frequency domain data, which are useful to calculate the values of ship capsizing such as l and l_{max}.

Table 1 Load experiment results

Counterweight (kg)	v (Hz)	v' (Hz)	l (m)	b (m)	l_{max} (m)	l/l_{max}	θ_{max} (deg)	h_{max} (m)	θ_{rms}	h (m)	$\theta_{rms}/\theta_{max}$
0	0.507	1.152	0.321	0.565	0.427	0.750	41.398	0.238	0.051	0.000293	0.0012
0.106	0.761	1.464	0.169	0.331	0.237	0.715	44.288	0.147	0.035	0.00012	0.0008
0.212	0.820	1.406	0.165	0.347	0.239	0.690	46.347	0.159	0.061	0.000212	0.0013
1	0.820	1.523	0.152	0.303	0.214	0.708	44.909	0.136	0.136	0.000413	0.0030
1.106	0.703	1.367	0.197	0.382	0.274	0.718	44.092	0.169	0.062	0.000239	0.0014
1.212	0.703	1.679	0.158	0.278	0.208	0.760	40.552	0.112	0.114	0.000318	0.0028
1.424	0.703	1.699	0.156	0.265	0.205	0.762	40.326	0.109	0.268	0.00073	0.0067
1.636	**Capsized**										

Table 1 presents results of all load experiments, including v and v' for each experiment. By calculation based on v and v', which are frequency-based data, the center of gravity height (l) and the maximum center of gravity height (l_{max}) of the ship scale model are obtained, as well as the transverse vibration distance (b) of the ship. Actually,l divided by $l_{max}$is the capsize risk. The root mean square value of the rolling motion angle (θ_{rms}) of the ship is also provided. Although θ_{rms} divided by θ_{max} is usually an indicator for assessing capsize risk, in this series of experiments,θ_{rms} divided by θ_{max} is too small to serve as a reliable indicator of capsize risk.

2.3 Height change experiment

The author used a 1 kg weight to simulate the ship load weight and used an air pump as a wave generator to create continuous and stable waves. The motion sensor remained in the middle of ship scale model.The ship motion simulated motion on the water surface. Data related to the ship's motion on the water surface were collected using motion sensors. Starting from the 0.07 m and gradually lifting the shelf of the ship scale model in every 0.01 m until 0.18 m shown in Figure 6 when the capsizing process occurred, one can observe the ship’s motion status, and can calculate the ship's motion frequency using fast Fourier Transform

(FFT) to calculate data related to the capsizing risk, such as the height of ship's center of gravity. For every 0.01 m increase, a considerable change occurred in the motion of the ship's proportional model. In this way, this parameter can change the height of center of gravity directly. The ship scale model motion is easier to obtain.

Figure 6 Lifting the shelf from 0.07 m to 0.18 m by 0.01 m increments

Capsizing occurred at 0.18 m of the shelf height. In the height changing experiment capsizing process, the capsizing speed was much faster than the load experiment capsizing speed. The speed of the entire capsizing process increases rapidly with the increase of capsizing angle, and in just 2 s, the ship scale model capsized completely.

Motion sensor recorded the time domain data of ship scale model motion. After FFT, the time domain data became frequency domain data, which are useful to calculate the values of ship capsizing.

Table 2 Height change experiment results

Counterweight Height (m)	v (Hz)	v' (Hz)	l (m)	b (m)	l_{max} (m)	l/l_{max}	θ_{max} (deg)	h_{max} (m)	θ_{rms}	h (m)	$\theta_{rms}/\theta_{max}$
0.07	1.035	1.679	0.110	0.239	0.162	0.677	47.344	0.112	0.134	0.000304	0.0028
0.08	1.035	1.777	0.103	0.217	0.150	0.691	46.319	0.100	0.213	0.000462	0.0046
0.09	0.703	1.152	0.236	0.509	0.347	0.679	47.162	0.238	0.111	0.000563	0.0023
0.10	1.035	1.582	0.117	0.265	0.177	0.663	48.438	0.126	0.137	0.000359	0.0028
0.11	0.898	1.718	0.122	0.240	0.171	0.714	44.381	0.107	0.172	0.000416	0.0039
0.12	0.820	1.894	0.120	0.210	0.160	0.753	41.097	0.088	0.065	0.000141	0.0016
0.13	0.703	1.464	0.183	0.340	0.249	0.732	42.879	0.147	0.130	0.000449	0.0030
0.14	0.722	1.445	0.181	0.344	0.249	0.724	43.595	0.151	0.289	0.001005	0.0066
0.15	0.546	1.152	0.299	0.551	0.406	0.735	42.680	0.238	0.286	0.0016	0.0067
0.16	0.507	1.464	0.249	0.380	0.313	0.794	37.400	0.147	0.132	0.000527	0.0035
0.17	0.390	1.191	0.397	0.587	0.494	0.803	36.507	0.223	0.241	0.001473	0.0066
0.18	**Capsized**										

Table 2 presents the results of all height change experiments. Based on v and v', by calculating and summarizing the data related to capsizing, the results of capsizing risk (l/l_{max}) are clarified. The height of the center of gravity (l) and the maximum height of the center of gravity (l_{max}) clearly show significant changes. The risk of capsizing increases with the increase of height of the counterweight (load weight on the shelf). The maximum capsizing angle (θ_{max}) that the ship scale model can withstand shows a decreasing trend. In the height change experiment, h is still very small. It shows a marked numerical difference from h_{max}. Therefore, it will not have a strong effect on the ship. In these height changing experiments, θ_{rms} divided by θ_{max} is still too small to serve as a reliable indicator of the capsize risk.

III. RESULTS AND DISCUSSION

3.1Loadexperimentresults

The author summarized and analyzed several sets of load experiment results as shown in Table 1, with plots of necessary data.

According to Figure 7, the ship scale model has a very high center of gravity height when unloaded. However, as the load increases, the center of gravity height decreases and does not change much. The maximum center of gravity height also varies with the change of center of gravity height, which was always higher than the center of gravity. With the load weight increase, a small change occurs between the center of gravity height and the maximum center of gravity height. The distance between the center of gravity height and the maximum center of gravity height becomes smaller and smaller, reflectingthat the risk of capsizing increases gradually.However, the center of gravity height is still lower than the maximum center of gravity height. Therefore, it seems that there is no high risk of capsizing unless the center of gravity height is equal to the maximum center of gravity height or higher than the maximum center of gravity.

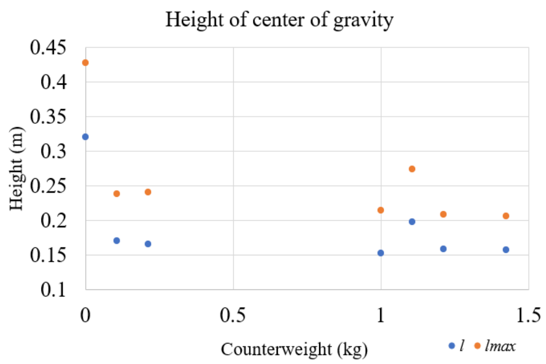

Figure 7Height of center of gravity of load experiment

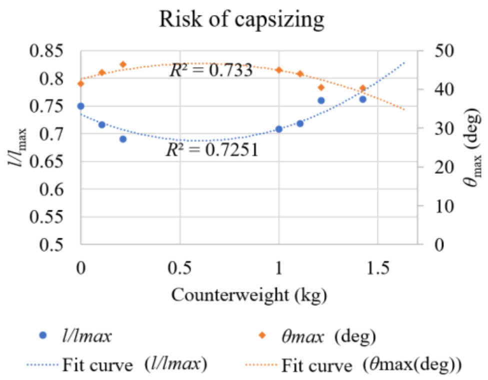

Figure 8Capsizing risk load experiment

Based on Figure 8, l divided by$l_{\max}$ represents the risk of capsizing, it is apparent that the capsizing risk trend is first decreasing and then increasing, whereas the maximum capsizing angle is first increasing and then decreasing. These two variables show an inverse trend of change. However, the trend of changes in the risk of capsizing is less smooth than the maximum capsizing angle that the ship scale model can withstand. Its value of change of maximum capsizing angle is not as great as that of the capsizing risk. The change in numerical values can also reflect the capsizing risk to some degree. Considering these two evaluation criteria related to ship capsizing, the ship's stability increases to some degree under certain loading conditions. However, when the cargo load exceeds a certain limit, the ship's stability deteriorates: the capsizing risk increases gradually.The maximum capsizing angle it can withstand decreases gradually.

3.2Height changing experiment results

After summarizing and analyzing the sets of height change experiment resultspresented inTable 2, the necessary data related to capsizing can be plotted.

According to Figure 9, it is readily apparent that the height of the center of gravity and the maximum height of the center of gravity both increase as the height increases. However, within the height range of 0.07–0.12 m, no significant change was found in either the center of gravity height or the maximum center of gravity height of the ship model used for experimentation.The differences between the two presented no clear pattern. By contrast, both the center of gravity height and the maximum center of gravity height rose sharply when the shelf height of the ship model increased to 0.13–0.17 m.

Based on Figure 10, it can be inferred that the risk of capsizing increases. The maximum capsizing angle decreases, showing an inverse ratio. Agreater height of the weight is associated witha greater change in the center of gravity. The risk of capsizing shows a similar exponential increase.

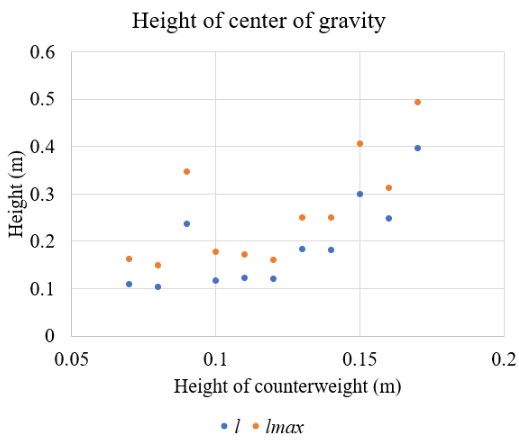

Figure 9Height of center of gravity of height changing experiment

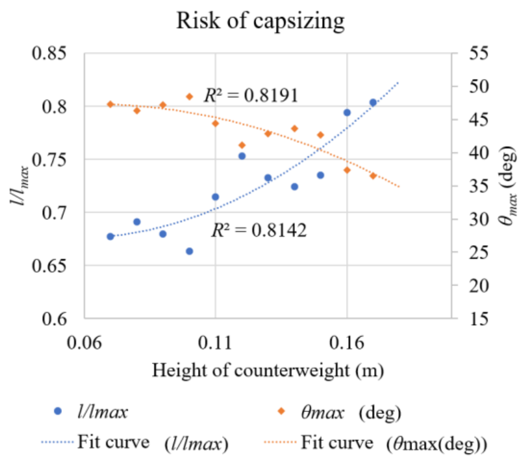

Figure 10Risk of capsizing in height changing experiment

3.3Discussion

The experiments described herein did not specifically examine the loading conditions of the ship to assess whether capsizing accidents occur over time. Instead, it investigated the risk of ship capsizing under unknown information, parameters, and conditions by altering the height of the ship's center of gravity. Earlier experiments and research changed not only the load height but also the load weight, while observing the ship's movement over time and increasing the load weight continuously until a capsizing accident occurred. The main difference between this study and earlier experiments is that the controlling of the load height and load weight were the only independent variables in the two sets of experiments. No comparison was made between the two sets of experiments, but the results demonstrate better that using the D3DCG method facilitates detection and estimation of the risk of ship capsizing under any conditions.

Based on results obtained from these two experiments, an important finding is that although the loading conditions differed between the experiments, capsizing occurred in both experiments when the l/l_{max} reached about 0.8. Therefore, l/l_{max}=0.8 can be inferred as a useful alarm index to prevent capsizing.

In global logistics, ship transportation has always been an indispensable mode of transport because it can convey large cargoes inexpensively. However, to prevent ship capsizing accidents at this stage, one must understand the ship's information, specific parameters, and cargo loading status. Moreover, one must even predict the climatic conditions along the route to prevent capsizing caused by wind and waves. Those requirements make prediction and prevention of ship capsizing very complex and requireconsiderable financial support. The methodto prevent ship capsizing proposed herein can greatly reduce costs while simultaneouslyproviding benefits in terms of accuracy and efficiency. For example, the AIS or radar of small and medium-sized vessels such as fishing boats and speedboatsdo not store the various parameters of this type of vessel, making it difficult to assess its capsizing risk. The salient benefit of D3DCG is its low cost, which is useful as an anti-capsizing method for ships of these types. An additionalbenefit is that no need exists for any shipinformation or parameters such as load capacity: only the frequency of ship motion is used to calculate l, l_{max}, and θ_{max}, which are related to ship capsizing.

IV. CONCLUSIONS

This study was conducted to ascertain the risk of capsizing and the maximum capsizing angle that a ship can withstand based on its motion state when the ship type and loading status are unknown. This information might provide a new method for estimating and predicting ship stability on a water surface and whether a risk of capsizing exists. Whether it is during the ship docking or navigation, in the event of other accidents, it can provide simpler and more intuitive understanding of the ship's movement status, thereby allowing ship drivers to take emergency measures more quickly. At the same time, it is possible to calculate the real-time wave height borne by the ship to ascertain whether the wave height affects the capsizing of the ship. Understanding the real-time wave height is crucially important: first, it can evaluate the ship stability in different sea conditions more accurately, helping to predict and prevent potential capsizing accidents. This method can also provide a better basis for ship navigation and loading decisions, thereby improving overall maritime safety. In addition, assessing and mitigating the capsizing risk can help reduce the loss of life and property associated with such accidents. Finally, preventing ship capsizing is crucially important for protecting the marine environment from pollution and ecological damage caused by ship wreckage and leaked cargo. Understanding the real-time wave height experienced by ships can lead to better assessment of the capsizing risk based on wave movement, to reduction of losses of life and property caused by ship capsizing accidents, and to protection of marine environments.

As described herein, through these series of experiments, findingshave demonstrated that the real-time wave height of the ship scale model is very small. It has almost no marked change, which has little effect on the capsizing of the experimental ship scale model.

Future studies must be conducted for detection of real-time wave height to ascertain the extent of its effects on ship capsizing accidents in open areas of water, including wind and othercontributingfactors.

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