An Investigation into the Capsizing Accident of a Pusher Tug Boat

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ABSTRACT

This paper outlines a technical investigation into an accident of a pusher tug boat, which capsized whilst navigating near the outer boundary of Seto Inland Sea, Japan on 27 May 2013. In order to clarify the relation between rudder angle and heel angle in the manoeuvring motion of the capsized boat, an experiment using an actual similar boat was carried out. Utilising the experimental results and a stability calculation of the boat at the accident along with a statistically estimated roll angle in the waves at that time, a mechanism of capsizing was identified from energy balance like the IMO weather criterion concept.

Keywords: *accident investigation, pusher tug boat, capsizing, experiment with an actual boat, heel due to manoeuvring*

1. INTRODUCTION

A typical Japanese pusher tug boat "No. 38 Sankyo Maru" capsized off Awaji Island in Seto Inland Sea on 27 May 2013. The accident claimed two lives of crew on board. The Japan Transport Safety Board (JTSB) had investigated this accident and identified probable causes of the accident. The results of the investigations were compiled into an investigation report and submitted to the Minister of Land, Infrastructure, Transport and Tourism and publicized (JTSB, 2014).

As a technical part of the investigation, the National Maritime Research Institute (NMRI) carried out a manoeuvring experiment using an actual similar boat and utilising the experimental results a mechanism of capsizing was examined along with a stability calculation. Based on the technical investigation the JTSB concluded the probable causes of the accident and issued recommendations in order to prevent similar accidents.

In this paper the main points of technical investigation are presented.

2. OUTLINE OF THE ACCIDENT

2.1 Summary of the Accident

"No. 38 Sankyo Maru" whilst returning to Osaka from Tokushima without a box barge capsized off Awaji Island around 15 o'clock on 27 May 2013. Two members of the crew in the bridge died and a skipper in the cabin inside the hull was rescued from the capsized boat. A high sea warning was issued at that time. The estimated wind and sea conditions at the time of the accident are summarised in Table 1.

According to the skipper, who took a nap at the accident, the boat suddenly heeled to the port side largely then capsized in a short time. But sequence and mechanism of the accident were not clear.

Table 1. Wind and Sea Conditions at the Accident.

Average wind speed	about 7 m/s ~ 8 m/s
Wind direction	SSW
Significant wave height	about 2 m ~ 3 m
Average wave period	about 5 s
Wave direction	S

2.2 Capsized Pusher Tug Boat "No. 38 Sankyo Maru"

"No. 38 Sankyo Maru" (Lr = 16.00 m, B = 5.50 m and D = 2.00 m) constructed in 2007 was a twin-propeller and twin-rudder pusher tug boat of 19 gross tons. The general arrangement of the boat is shown in Figure 1.

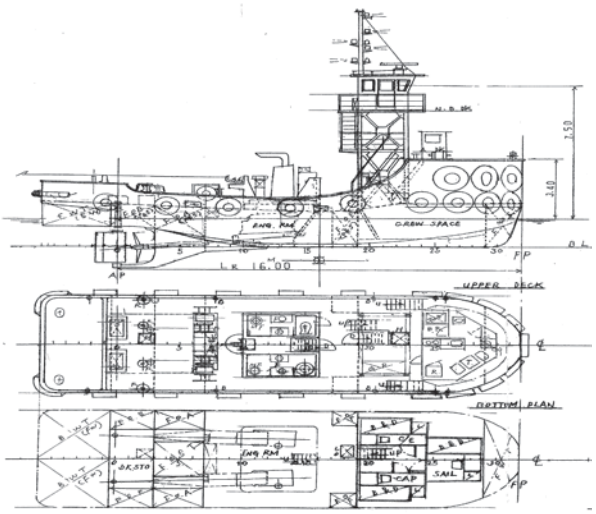

Figure 1 General Arrangement of "No. 38 Sankyo Maru".

In order to secure enough manoeuvrability during linking with a box barge the rudder area ratio of the boat was relatively large and even with small rudder angle its steering quality was good. However, relatively large rudder area also led to inducing large heeling moment in manoeuvring motion. Therefore, during navigating without a box barge in order to prevent large heel in changing course the skipper used to limit the rudder angle to about 5 degrees and ease the wheel immediately. And he instructed the crew to follow his way of steering the boat.

3. AT-SEA EXPERIMENT

Due to the above mentioned feature of the capsized boat it was presumed that heel angle in manoeuvring motion might be related to the occurrence of the accident but its characteristic was unknown. Therefore, in order to clarify the relation between rudder angle and heel angle in manoeuvring motion of the capsized boat, an experiment using an actual similar boat was carried out. From the experimental results an estimation method for heel angle of the capsized boat in manoeuvring motion was derived.

3.1 Outline of the Experiment

A twin-propeller and twin-rudder pusher tug boat "No. 58 Sankyo Maru" whose principal particulars, rudder area and output of main engines were the same as for the capsized boat was used in the experiment. At the experiment the boat was almost full loaded with fuel oil and fresh water.

Table 2. Hull Condition at the Experiment.

Displacement: W	141.31 t
Mean draft: d	1.69 m
Trim by stern: τ	1.11 m
Vertical C.G.: KG	1.99 m
Metacentric height: GM	0.76 m

An inclining test was carried out first to clarify the condition of the boat at the experiment and the result (Table 2) was used to estimate the condition of the capsized boat at the accident. Then, a manoeuvring experiment was carried out and the boat motion (roll angle, yaw angle, yaw rate and so on) and the boat speed were measured. In the experiment not only rudder angle but also way of steering was changed (Table 3).

Table 3. Summary of the experiment

Kind of test	Turning test, weave manoeuver test.
Approach speed	9 kn, the same as the presumed speed of the capsized boat at the accident.
Rudder angle (degrees)	(1)Turning test 5, 8, 10 (port), 10 (stbd.).
	(2) Weave manoeuver test 7(port)-7(stbd.)-8(port)-6(stbd.), 9(stbd.)-8(port)-9(stbd.)-9(port), 10(port)-9(stbd.)-12(port)-12(stbd.), 13(port)-10(stbd.)-10(port)-13(stbd.), 22(stbd.)-17(port)-23(stbd.)-7(port).

3.2 Experimental Results

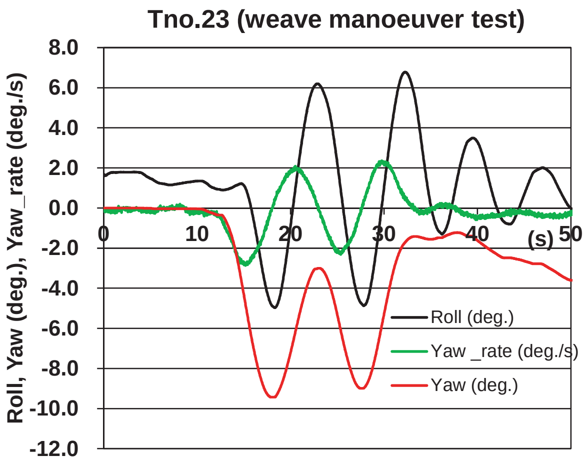

Figure 2 Measured roll angle, yaw angle and yaw rate in a weave manoeuver test with a series of rudder angles of 13(port)-10(stbd.)-10 (port)-13(stbd.) degrees.

Figure 2 shows an example of measured time histories of roll angle, yaw angle and yaw rate in a weave manoeuver. Roll angle is positive for the port side down and yaw angle and yaw rate are positive for a starboard turn. From the measured boat motion and observation during the experiment the characteristic of heel angle in manoeuvring motion of the similar boat could be summarised as follows (refer to Figure 2).

(1)No clear inward heel occurs in the initial stage of manoeuvring motion.

(2)Corresponding to the magnitude of rudder angle relatively large outward heel occurs during manoeuvring motion.

(3)Response speed of heel to steering is relatively fast and outward heel develops quickly.

Heel Angle. Figure 3 shows relation between heel angles and rudder angles measured in the experiment. The horizontal axis is rudder angle δ, positive for the starboard side, and the vertical axis is outward heel angle ϕ_2, positive for the port side down. From Figure 3 it is noticed that within the measured extent the relation between heel angles and rudder angles is approximated by a linear function (showed in the dotted line) and in manoeuvring motion of the similar boat outward heel of almost half as large as rudder angle is induced.

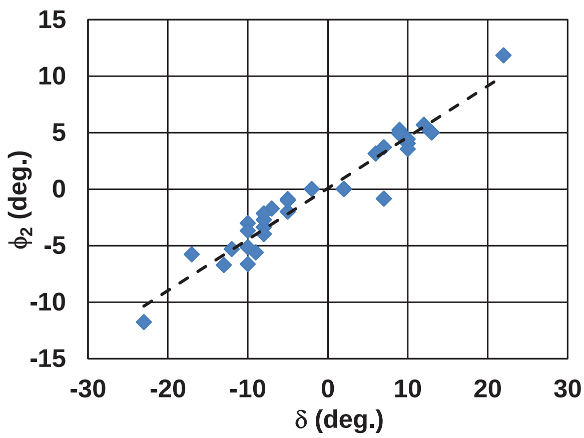

Figure 3 Measured heel angles and rudder angles in the experiment.

Turning Rate. Figure 4 shows the relation between turning rates (yaw rates) and rudder angles measured in the experiment. The vertical axis is normalised turning rate *r'*, which is positive for a starboard turn. The normalised turning rate *r'* was calculated with equation (1).

$$r' = \frac{L_{pp}}{r} = \frac{\omega \cdot L_{pp}}{V} \quad (1)$$

where ω is the measured turning rate, V is the measured boat speed, r is the local radius of trajectory and L_{pp} is the length between perpendiculars of the boat.

From Figure 4 it is noticed that within the measured extent the relation between normalised turning rates and rudder angles is approximated by a linear function as equation (2) (the dotted line in Figure 4).

$$r' = 0.0122 \times \delta - 0.0078 \quad (2)$$

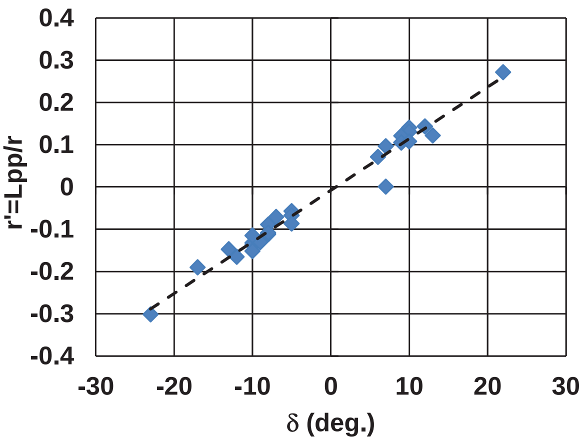

Figure 4 Measured turning rates and rudder angles in the experiment.

3.3 Estimation of Outward Heel Angle of the Capsized Boat

Outward heel in manoeuvring motion is induced by a couple consisting of a centrifugal force acting on the centre of gravity and a fluid reaction force acting on the side of hull. If the fluid reaction force is assumed to act at half the mean draft (d/2), outward heeling moment M is estimated with equation (3) (Morita, 1985).

$$M = \frac{W}{g}\frac{V^2}{r}\left(\overline{KG} - \frac{d}{2}\right) \quad (3)$$

where W is the displacement of the boat, g is the gravitational acceleration, KG is the vertical centre of gravity of the boat.

Figure 5 shows a comparison between the outward heeling moments estimated by substituting experimental data in equation (3) and the righting moments corresponding the measured heel angle, $W \bullet GM \bullet \sin\phi_2$. From Figure 5 it is noticed that the righting moment is almost 2.77 times (the dotted line in Figure 5) larger than the outward heeling moment estimated with equation (3). This indicates that for the similar boat the fluid reaction force acts at a position, which differs largely from half draft (d/2). And in addition to this due to inertia of the boat and change in rudder force at reversing rudder angle in weave manoeuver might increase the outward heel angle.

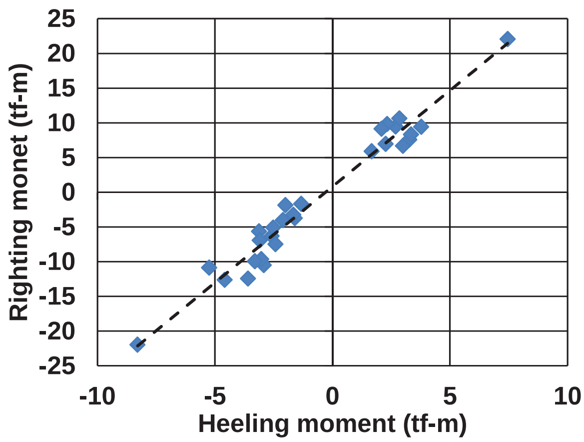

Figure 5 Outward heeling moments estimated with equation (3) and righting moments corresponding to measured heel angles.

If the following are supposed, outward heel angle ϕ_2 of the capsized boat in manoeuvring motion for given rudder angle δ can be estimated with equations (2), (4) and (5).

(1)Turning characteristics, the relation between rudder angle and turning rate, of the capsized boat at the accident is the same as the similar boat at the experiment (Figure 4).

(2)Speed reduction in manoeuvring motion is negligible.

(3)Feature of outward heeling moment of the similar boat at the experiment (Figure 5) is applicable to the capsized boat at the accident.

$$r = \frac{L_{pp}}{r'} \tag{4}$$

$$\sin\phi_2 = 2.77 \times \frac{V^2}{g \cdot r \cdot \overline{GM}}\left(\overline{KG} - \frac{d}{2}\right) \tag{5}$$

4. CONSIDERATION ON CAPSIZING MECHANISM

As the high sea warning was issued at the time of the accident and for the capsized boat quite careful steering was necessary to prevent large heel in changing course during navigating without a box barge , it is presumed that the following factors, wind and waves at the accident and careless steering of the boat, were related to the accident. As the skipper explained that the boat suddenly heeled to the port side largely then capsized in a short time, the situation of occurrence of the capsizing was supposed to be similar to that of the IMO weather criterion. Therefore, with calculating maximum heel angle based on an energy balance concept like the weather criterion, the capsizing mechanism was examined.

4.1 Stability at the Accident

Table 4 shows the estimated loading condition of the boat at the time of the accident, which is based on the inclining test result of the similar boat and the fuel oil and fresh water, supposed to be loaded into the capsized boat at the accident. Stability calculation was carried out with trim free condition. Figure 6 shows the stability curve at the time of the accident and Table 5 shows the estimated draft, trim, metacentric height and angle of bulwark top immersion. In Figure 6 the stability curve of the similar boat at the experiment is also shown.

From Figure 6 and Tables 2, 4 and 5 it is noticed that as the full loaded fuel oil and fresh water increase the draft and trim of the boat, for large heel angle the stability of the similar boat at the experiment is smaller than that of the capsized boat at the accident. Therefore, for pusher tug boats of similar type to the capsized one, in order to maintain sufficient stability special attention is needed in loading fuel oil and fresh water.

Table 4. Loading condition at the accident.

Displacement: W	129.21 t
Vertical C.G.: KG	2.03 m
Longitudinal C.G.: mid-G	-1.19 m
Free surface effect: GG_0	0.11 m

Table 5. Draft, trim, metacentric height and angle of bulwark top immersion at the accident.

Mean draft: d	1.66 m
Trim by stern: τ	0.37 m
Metacentric height: G_0M	0.70 m
Angle of bulwark top immersion: ϕ_b	20.7 deg.

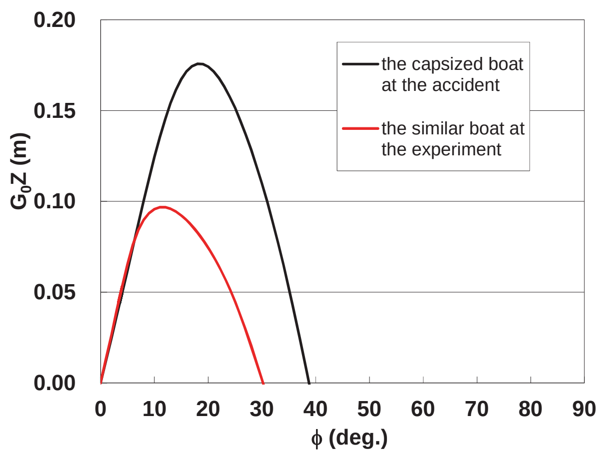

Figure 6 Stability curves at the accident and at the experiment.

4.2 Influence of Wind and Waves

<u>Heel due to the Wind at the Accident.</u> Assuming beam wind condition, heel angle under action of steady wind and gust wind at

the accident were estimated with the same method as the weather criterion except wind pressure at 8 m/s. Table 6 shows the estimated heel angles due to the wind at the accident. Even gustiness considered, the heel angle due to the wind at the accident is estimated to be less than 1 degree. Taking the stability curve at the accident, Figure 6, into account, influence of the heel due to the wind at that time on the capsizing of the boat would be quite small. Therefore, the influence of the wind was excluded from consideration on capsizing mechanism.

Table 6. Heel angle due to the wind at accident (steady wind speed of 8 m/s).

Lateral windage area: A	49.06 m^2
Vertical distance from centre of “A” to a point at half the mean draft: Z	2.82 m
Wind pressure at 8 m/s: P	47.7
Heeling lever due to steady wind: l_{w1} = PAZ/1000gW	0.005 m
Heeling lever due to gust wind: $l_{w2} = 1.5 l_{w1}$	0.008 m
Heel angle due to steady wind: ϕ_0	0.44 deg.
Heel angle due to gust wind: $1.5\phi_0$	0.65 deg.

Roll due to the Waves at the Accident. It was presumed that the speed of the boat was 9 knots and its heading angle was about 60 degrees at the time of the accident. Based on this information and the estimated sea condition at the time of the accident, Table 1, roll response of the capsized boat in a short crested sea was statistically estimated with the condition that the significant wave height was 2 m, the average wave period was 4.8 s and the mean encounter angle was 60 degrees. As a result, the expected largest in 200 successive roll amplitudes, ϕ_1 of the capsized boat is estimated to be 15.6 degrees (Table 7). Considering the stability at the accident, the estimated roll in the waves at the accident should be one of main factors related the capsizing of the boat.

As shown in Table 7, the expected largest in 200 successive roll amplitudes of the similar boat in the wave at the accident is 6.2 degrees, which is less than half that of the capsized boat. However, considering the stability of the similar boat at the experiment, the estimated roll angle in the waves at the accident might impair its safety.

Table 7. Roll angle of 1/200 maximum expectation in waves at the accident.

The capsized boat at the accident	15.6 deg.
The similar boat at the experiment	6.2 deg.

4.3 Influence of Steering

No information on the way of steering the capsized boat at the accident was provided. Therefore, outward heel angle ϕ_2 of the capsized boat at speed of 9 knots in manoeuvring motion with rudder angle of 5 to 15 degrees was estimated with equations (2), (4) and (5). Figure 7 shows the estimated outward heel angle due to steering of the capsized boat along with that of the similar boat at the experiment.

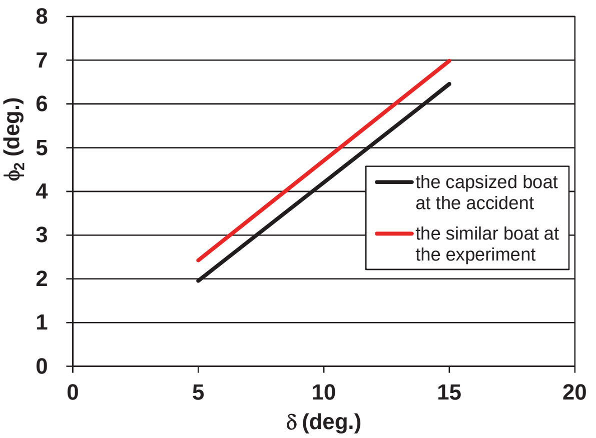

Figure 7 Outward heel angle due to steering.

The outward heel angle of the capsized boat at the accident is smaller than that of the similar boat at the experiment. At the condition of the accident the outward heel angle of the capsized boat with rudder angle of 10 degrees is estimated to be 4.2 degrees, which is much smaller than the estimated roll angle in the waves at the accident. However, during steering the capsized boat outward heeling moment was supposed to keep working at the accident. In that case the outward heeling moment should reduce the residual dynamical stability of the capsized boat significantly.

4.4 Consideration on Capsizing Mechanism

As mentioned above it was presumed that rolling in waves at the accident and outward heel due to steering played a key role to the capsizing of the boat. Therefore, assuming that the capsized boat rolling in waves was carelessly steered at the accident, the mechanism of the capsizing was examined by calculating maximum heel angle with an energy balance concept like the weather criterion. In the examination as the worst case, the capsized boat was assumed to suffer outward heeling moment induced by starboard steering when it rolled to starboard side at an angle corresponding to the 1/200 maximum expectation in the waves at the accident and energy balance between rolling energy and dynamical stability was calculated. As no information on the steering of the capsized boat at the accident was available, the energy balance calculation was carried out at various rudder angles. The rudder angles, which induced the bulwark top immersion and the capsizing, were estimated and their feasibility was considered.

Table 8. Calculation results

δ (deg.)	ϕ_2 (deg.)	$b(\phi_b)/a$	b/a	$\phi_{\_1}$ (deg.)
4.7	1.8	1.00	1.77	20.7
5.0	2.0	0.97	1.70	21.1
9.7	4.1	0.58	1.00	34.9

Calculation results are shown in Table 8 and graphs used for calculation are shown in Figure 8. In Table 8, ϕ_2 is the outward heel angle due to starboard steering with rudder angle of δ, “a” and “b” are the rolling energy to the port side (the capsizing direction) and the residual dynamical stability respectively (refer to Figure 8), “b (ϕ_b)” is the residual dynamical stability up to the angle of bulwark top immersion (refer to Figure 8) and $\phi_{\_1}$ is the maximum heel angle to the port side.

From Table 8 it is noticed that if the outward heeling moment induced by the steering with rudder angle of 4.7 degrees is assumed to act on the boat when it rolls to the starboard side at the maximum, the resultant port side heel reaches the angle of bulwark top immersion (ϕ_b), 20.7 degrees. If the assumed rudder angle is larger than 4.7 degrees, the maximum heel angle to the port side exceeds the angle of bulwark top immersion. For example with the assumed rudder angle of 5.0 degrees the maximum heel angle to the port side is 21.1 degrees, and the bulwark top is considered to be immersed. After the top of bulwark is immersed, it should induce a resistance force against up-righting the boat. Therefore, if the bulwark top is immersed the boat would not upright readily and the successive waves might capsize it. Table 8 also shows that if the assumed rudder angle of starboard steering at the accident is larger than 10 degrees, the boat is considered to capsize immediately to port.

Although during navigating without a box barge in order to prevent large heel in changing course steering with small rudder angle used to be carried out for the capsized boat, it seems not unrealistic to assume that steering with rudder angle of about 5 degrees was carried out at the accident. In any case the calculation results indicate that if the worst case that when the boat rolls to one side at the maximum heeling moment due to steering to the same side is assume to act on the boat, steering with rudder angle of less than 10 degrees could lead the boat to capsize. Therefore it seems that for pusher tug boats of similar type to the capsized one, careful steering with small rudder angle is indispensable to ensure safety during navigating without a box barge.

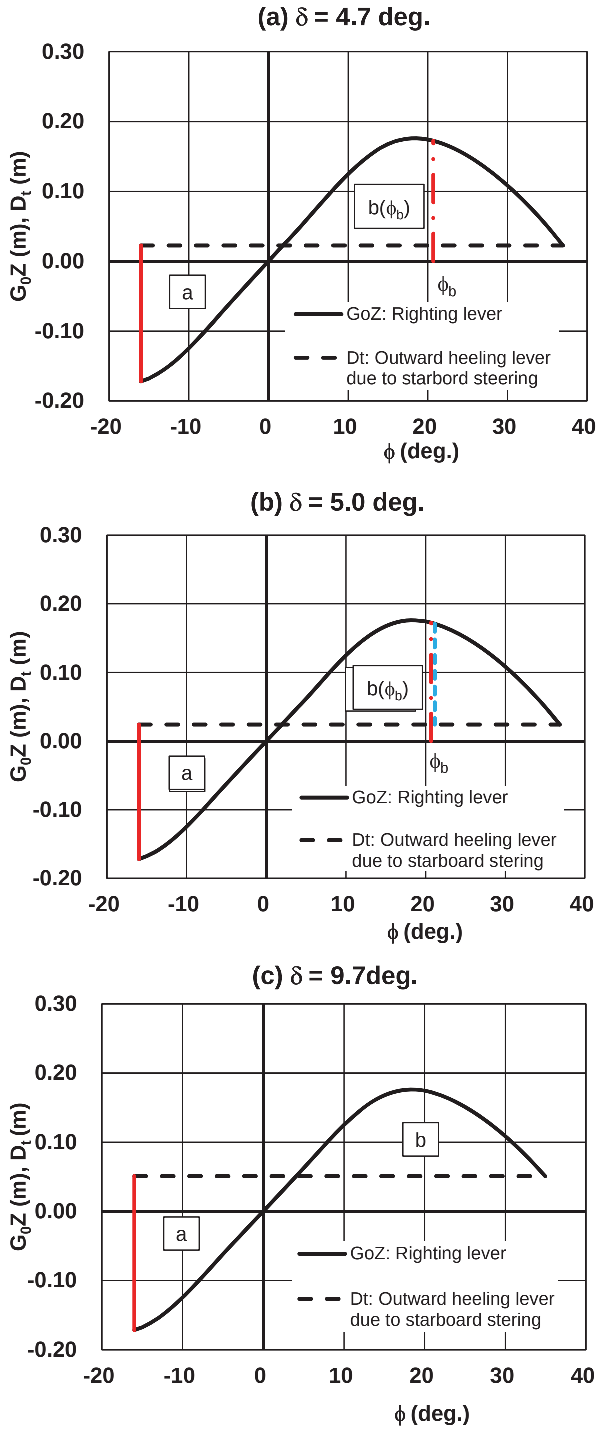

Figure 8 Comparison between dynamical stability and heeling energy with various rudder angles.

5. CONCLUSIONS

With the above mentioned technical investigation and so on the JTSB compiled the investigation report on the capsizing accident of "No. 38 Sankyo Maru" and publicised it (JTSB, 2014). In the report, the probable cause of the accident is summarised as follows. Due to the steering with rudder angle of larger than 4.7 degrees the capsized boat navigating without a box barge at speed of about 9 knots with suffering starboard waves of about 2 ~ 3 meters in significant wave height and about 5 seconds in average wave period was forced to heel beyond the angle of bulwark top immersion to the port side and fell into a difficult situation for up-righting. Then with successive waves action the boat might have capsized.

In the report the following feature of pusher tug boats of similar type to the capsized one are pointed out too.

(1) Depending on the loading condition of fuel oil and so on, the stability of these boats tends to reduce considerably.
(2) In rough weather large rolling due to waves may occur easily in these boats.
(3) As the rudders of these boats are designed to secure enough manoeuvrability during linking with a box barge, in case of navigating solely these boats are liable to heel largely by the action of rudders.

In order to prevent similar accident, the operating company is instructed to prepare a manual, which explains precautions for pusher tug boats in navigating solely, limitation on loading fuel oil and so on, wind and sea conditions where planed navigation should be abandoned, appropriate way of steering etc. and advise skippers to follow it.

6. REFERENCES

Japan Transport Safety Board, 2014, "Push boat SANKYO MARU No. 38 Capsizing", Marine Accident Investigation Report, MA2014-3 (in Japanese).

Morita, T., 1985, "Theory of Ship Stability - Basis and Application -", Kaibun-do, pp. 134-136 (in Japanese).