

SEWOL FERRY CAPSIZING AND FLOODING

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SUMMARY

The capsizing and sinking of Sewol close to the South Korean coast in fair weather on April 16, 2014 caused the death of 304 people. In December 2017 the Sewol Investigation Commission of South Korea contracted MARIN to conduct an extensive investigation into the turning, capsizing, flooding and sinking of the vessel.

Systematic tests with a 1:25 model of the vessel were conducted for more than 340 turning and heeling scenarios in MARIN's Seakeeping and Manoeuvring Basin. These cases consisted of variations in transverse stability, propulsion, steering and fin stabilisation. The effects of moving cargo and possible external forces were included during the free sailing model tests featuring five active control systems. The human factor in possible steering actions was investigated in a full mission wheelhouse simulator.

For the flooding tests a 1:30 carbon model was manufactured and equipped. The water tight compartments were modelled and relevant inflow openings, ventilation openings, ducts, hatches and doors were included in the scale model. Flooding tests were conducted in a controlled manner by using a captive model set-up utilising a hexapod actuator to force the vessel in the trajectory observed during the accident. The forces required to constrain the model were measured and showed the balance between the inflowing water and the instantaneous displacement of the vessel. The flooding tests were conducted in the Depressurised Wave Basin to reduce possible scale effects. With these captive tests the most likely scenario of flooding was determined. Finally, flooding and sinking tests were also performed with the model in free floating atmospheric condition.

The results of this investigation inspired additional research into the stability of passenger vessels leading to a submission to IMO MSC for improvement of the Intact Stability Code 2008.

1. INTRODUCTION

On the 16th of April 2014, on her way from Incheon to Jeju-island under calm weather conditions, the Korean ferry SEWOL (Figure 1) turned, capsized, flooded and sank one nautical mile off the coast of Donggeochado, Jindo County, South Korea. In total 304 people including 250 secondary school students, other passengers and several crew members, did not survive this national disaster. In December 2017, the Sewol Investigation Commission (SIC) of Korea contracted MARIN to investigate the turning, heeling, flooding and sinking of the vessel by means of computer simulations, model tests and nautical simulators.



Figure 1: Picture of the port side of Sewol ferry

M/V SEWOL was a double screw-single rudder coastal ferry with a length of 146 m, designed and constructed by a Japanese shipyard. Launched in 1994 the vessel was in service in Japan for 18 years. In 2012 the ferry was purchased by a Korean owner, converted for the Incheon-Jeju service and registered under Korean flag as a coastal ferry. The main dimensions of the vessel and her loading

condition during the accident as estimated by SIC are presented in Table 1.

SEWOL was not equipped with a loading computer nor with a Voyage Data Recorder. Output from a course/rudder recorder was not provided. Time step positions and headings of the vessel however, were transmitted by her Automatic Identification System (AIS). Furthermore SIC was able to derive the heel of the vessel from the data recorded by various dash cams mounted in the vehicles on board the vessel.

Dimension	Unit	Sewol ferry
Length over all	m	145.6
Length between perpendiculars	m	132.0
Beam	m	22.0
Draught forward	m	5.9
Draught aft	m	6.4
Draught mid-ship	m	6.15
Displacement volume	m ³	9666
Displacement mass	ton	9918
Number of revolutions	rpm	140
Number of propellers		2
Diameter of propellers	m	4.4
Number of rudders		1

Table 1: Main particulars Sewol

In addition SIC supplied MARIN with the following collected information on the observed events:

- On April 15 at 9 p.m., the ferry left the port of Incheon several hours delayed due to fog,
- On April 16 at 8 a.m., the vessel navigated in approximately 40 m water depth and calm weather at a speed of approximately 18 knots,
- The AIS-track data indicates a sharp turn of the vessel to starboard around 8:49 a.m. In this turn the vessel heeled strongly over her port side,
- Based on the sounds recorded by dash cams, cars and containers started to slide at a vessel heel of approximately 18 degrees,
- Based on the data recorded by dash cams, cargos on the C-deck started to shift at a vessel heel of 33 degrees,
- Approximately 56 seconds after the estimated start of the turn, the heel of the vessel amounted to 45 degrees,
- The main engines were stopped; the vessel continued to drift under excessive list,
- The vessel flooded progressively and sank.

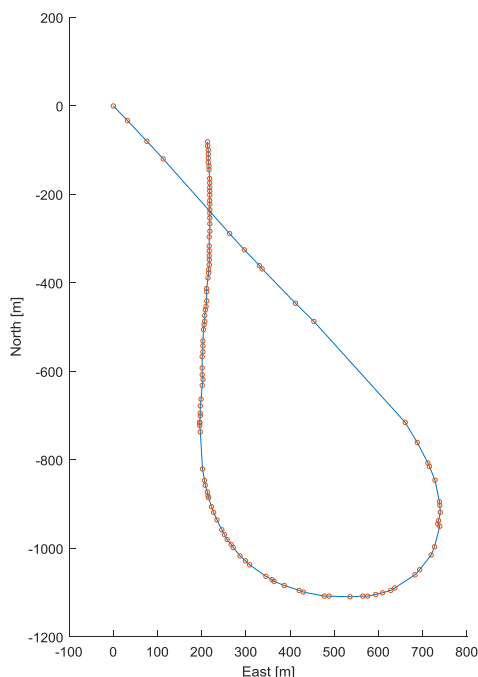
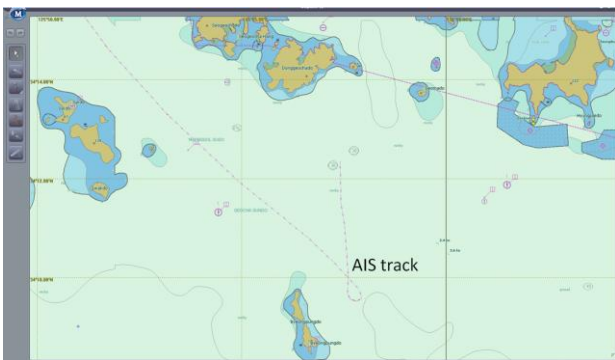


Figure 2: Vessel position received from AIS

The vessel position was transmitted by the AIS and received at irregular intervals (Figure 2). This track clearly shows the sudden turn of the vessel and, after capsizing, her drifting in northerly direction due to the current. The magnitude and direction of the current was derived from this drift path.

The heading of the vessel as received from AIS showed deviations from a smooth curve. The External Force Task Force within SIC derived extreme high rates of turn of the vessel (up to 15 degr/s) from this raw AIS heading signal. Based on these high rates, it was suggested that an external force could have been the cause of the accident although no other ships or objects in the area were reported and the local water depth was approximately 40 m.

The observations of SIC lead to the following questions to be answered by this investigation:

- How sensitive is the turning and heeling of the vessel to differences in initial transverse stability, initial heel, current gradients and possible external loads?
- Which ship condition could have resulted in the sharp turn and critical heel angle when cargo starts to shift?
- What is the effect of shifting cargo on the heel angle?
- What is the effect of possible rudder actions to PS and SB on the heel angle during the turn?
- What is the effect of current gradients on the turn and the heel?
- How does the progressive and fast flooding of the vessel materialize?

To answer these questions, a two stage investigation programme was conducted. In the first stage the vessel is propelled and steered and during the turning she heels up to 45 degrees. In the second stage the engines are stopped and the vessel starts to drift with the current at a heeling angle of 45 degrees when she progressively floods, capsizes and eventually sinks. The investigation into the turning and heeling is thus separated from the investigation into the flooding of the vessel.

2. TURNING AND HEELING

2.1 TEST PROGRAMME

The turning and heeling behaviour of Sewol has been investigated by numerical simulations, systematic model tests and real time manoeuvring on a nautical simulator. First RANS CFD analysis for the specific hull shape under drift and heeling angles up to 20 degrees were conducted to compute the hydrodynamic loads on the hull. These loads were used to enhance the general manoeuvring model specifically for the Sewol hull to simulate the effects of stability level variations and sequences of rudder commands. It was acknowledged

that the CFD calculations for such large angles of heel and drift have not been validated and therefore the hydrodynamic loads derived for such conditions should be handled with care. Nevertheless the results clearly indicated the sensitivities of the vessel for initial stability and rudder angles. Based on these results a model test programme was developed to test the dominant parameters in further detail including the effects of shifting cargo.

For this purpose a carbon fibre 1:25 scale model was manufactured and equipped with five controlled active systems. The model was fully self-propelled with autopilot steering and active stabilising fins. The shifting cargos were modelled by four lumped masses each on a transverse track, moved by linear motors and controlled by computer using the measured heel angle as input. Effect of a possible external force was modelled by a thin wire connected from the stabiliser fin on port side to a controlled winch mounted on the basin carriage. The model was further equipped with sensors and data acquisition systems to measure the propulsion shaft torque and rpm, the rudder angle, the stabiliser fin angles, the excursions of the four moveable masses, the loads in the winch wire and the resulting vessel motions in all six degrees of freedom.

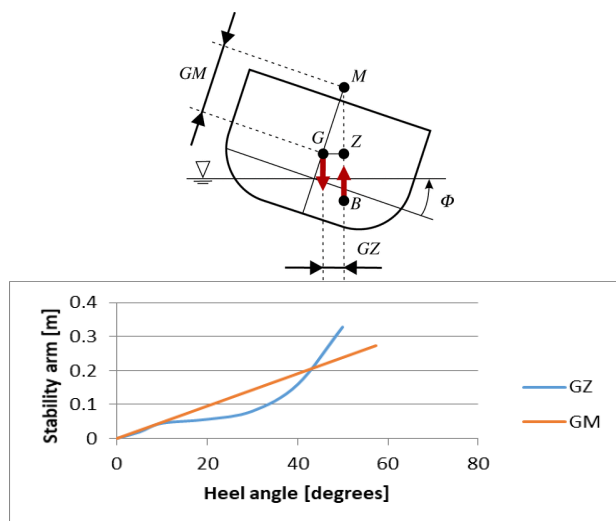


Figure 3: Effective arm of stability GZ compared with initial stability GM

As the transverse stability of Sewol during the accident was unknown, six levels of initial stability GM were defined by SIC for the tests. These ranged from GM = 0.60 m to GM = 0.01 m.

During the inclination tests of the model, it was noted that when the heeling angle exceeded 10 degrees, the restoring stability moment did not increase proportionally. In Figure 3 the effective stability arm GZ as function of heeling angle is presented. Up to 40 degrees of heel this effective arm is significantly lower than the initial stability value GM indicates. This is due to the shift of metacenter M caused by the 3-D geometry

of the submerged hull. The hull of Sewol is characterised by a slender bow section and a wide aft body featuring large recess areas for the external ramps. This recess is flooded at 10 degrees heel.

The turning and heeling tests were conducted in MARIN's Seakeeping and Manoeuvring Basin (170 x 40 x 5 m). The model was self-propelled and steered by autopilot. The only connection to the basin sub-carriage was the flexible power and signal cabling. The sub-carriage is able to move in transverse direction whereas the main carriage moves in longitudinal direction of the basin. By using the vessel position from the optical tracking system, the sub-carriage automatically followed the model in arbitrary horizontal directions (Figure 4).

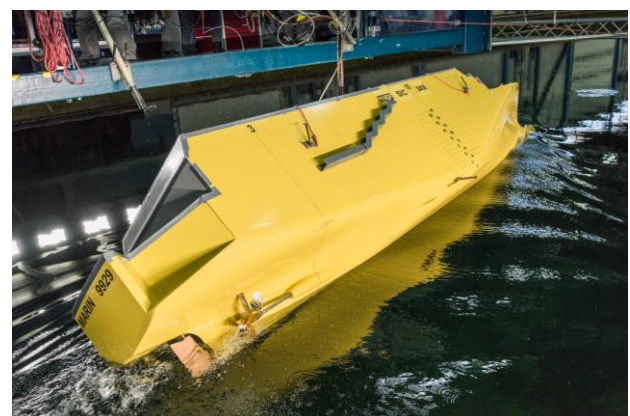
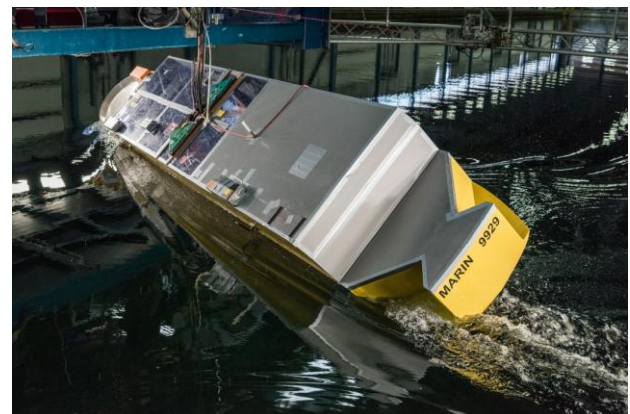


Figure 4: Sewol Model during Turning and Heeling tests

The test programme comprised speed-power tests, roll decay tests and standard manoeuvres such as zig-zag and turning circles to derive the manoeuvring characteristics of the vessel. The majority of the testing concerned the actual turning and heeling tests. Once the model had obtained the specified speed on a straight course, a sequence of rudder commands was given to the autopilot. More than 250 systematic variations in stability level, moving cargo weights, rudder angle sequences, propulsion and stabilising fin settings have been tested.

After analysis of the data and reporting of the results, SIC requested an additional test programme comprising more than 90 turning and heeling tests to investigate in further detail the effects of possible external forces, trim, pre-heel and initial vessel speed. These tests were conducted with the same model, test-set up and instrumentation.

2.2 RESULTS

Both the fast time manoeuvring simulations and model tests showed that the Sewol turning and heeling are strongly coupled. The turning of the vessel initiated by a rudder angle, inevitably leads to vessel heeling. As expected the maximum heel angle increased with decreasing transverse stability and increasing rudder angle. Approach speed had a similar effect on the ship motions; the yaw, yaw velocity, heel amplitude and rate of heel all increased. Heeling in a turn is thus governed by ship speed, rudder angle and the transverse stability (Figure 5).

The sliding and shifting of cargo obviously played a dominant role in the heeling and capsizing of Sewol. The heel angle threshold values as derived from the dash cams in the vehicles on board the ferry, were applied in the model tests including variations in delays, shifting speed and offsets. It was found that at a GM-value of 0.60 m the threshold value of 18 degrees was not reached even at high rudder angles. At a GM level of 0.06 m, this threshold was already reached at 5 degrees of rudder.

The model tests also demonstrated that trimming by the bow by 0.5 m, while maintaining the same vertical centre of gravity, results in a significant decrease of transverse stability. As illustrated by Figure 5 such trim by the bow results for a GM equal to 0.60 m in a heel of 25 degrees thus exceeding the 18 degrees threshold for cargo sliding. For an initial GM of 0.45 m the bow trim reduced the stability value to 0.23 m.

For low stability cases, the results of the turning tests proved to be sensitive for the starting conditions. A initial heel of 2 degrees to PS resulted in a different turn and heel than the run starting with 2 degrees inclination to SB.

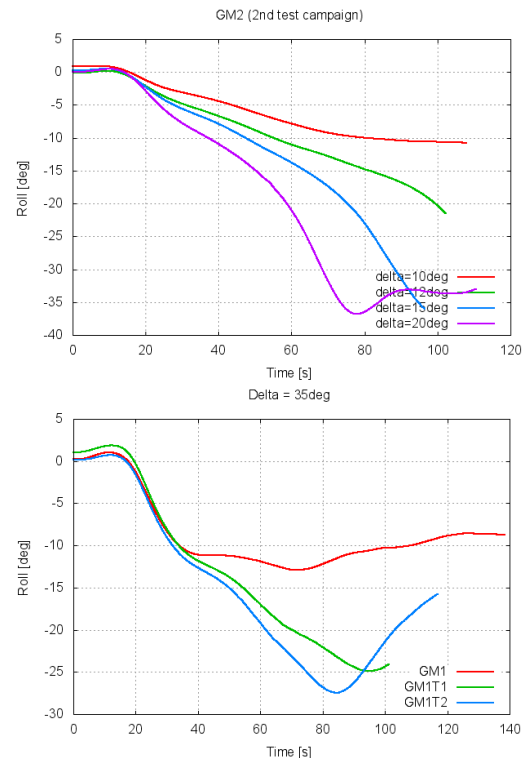


Figure 5: Influence of rudder and trim on heeling angle

As illustrated by Figure 6, several combinations of low transverse stability (GM between 0.1 and 0.3) and rudder angles (10 to 25 degrees) can result in a track which resembles the recorded AIS track of the vessel.

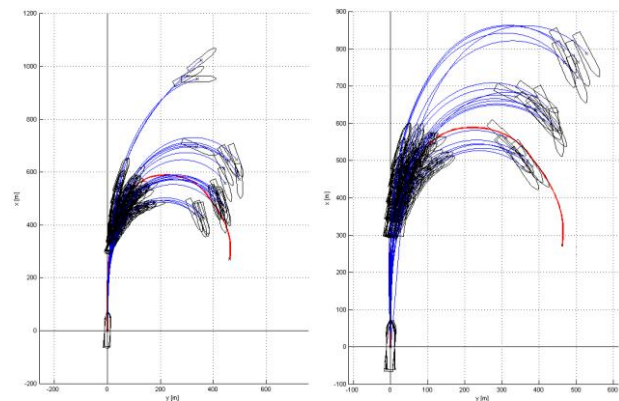


Figure 6: Model test results for GM2C (Left) and GM4B (Right) compared with AIS-track (red)

2.3 EXTERNAL FORCE

On request of SIC specific analysis and tests were conducted to investigate the effect of possible external forces on the rate of turn and the heeling of the vessel. Some derivation of the Rate of Turn from the AIS heading samples by the External Force Task Force within SIC, suggested extreme RoT values up to 15 degr/sec. RANS CFD analysis were conducted to compute the hydrodynamic forces acting on the vessel for such high rates of turn. To induce a RoT of 15 degr/s the analysis showed that an external force should have a magnitude in the order of 26 000 tonf. As the shaft of the stabilising fin

of Sewol did not sustain bending damage, it was agreed for the model tests to limit the magnitude of the external force to the yielding limit of the fin shaft which corresponds to a force of approx. 260 tonf.

In the turning and heeling tests this external force was applied by a carriage mounted winch via a thin wire connected to the port fin shaft. Extensive tests have been conducted for various combinations of winch force, direction and duration.

The maximum rate of turn achieved during those tests was 2.7 deg/s. This value was obtained using a winch force that increased the rate of turn but at the same time decreased the heel angle. None of the model tests resulted in the high rates of turn derived by The External Force Task Force within SIC from raw AIS heading data.

2.4 HUMAN FACTOR

To investigate the effect of human intervention in the turning and heeling of Sewol, a part of the investigation was conducted on MARIN's nautical simulator. In this full mission simulator, with 360 degrees surrounding view, the manoeuvring model was used at real time and received input from the helm and power settings controlled by the helmsman and captain in a full mock-up of the wheelhouse. Although the ship motions are only included in the outside view whereas the wheelhouse maintains a horizontal orientation, up to some 10 degrees of heel the simulator provides a realistic experience for the ship officers. The runs were conducted by experienced master mariners including members of SIC, assisted by a helmsman (Figure 7).

On the simulator various rudder commands were tested at the different levels of transverse stability. The resulting tracks were compared with the AIS positions received from Sewol. The simulator runs proved that even in the condition with extreme low initial stability ($GM = 0.01$ m), the vessel at 17 knots of speed was still controllable.



Figure 7: Run on the nautical simulator

3. FLOODING AND SINKING

3.1 TEST PROGRAMME

The second stage of the Sewol disaster concerned the time that the vessel listed 45 degrees with the engines stopped and seawater started to flood the vessel. This stage was investigated with model tests in both captive mode and in free floating mode. The flooding process was also simulated by means of a computer model.

To model the watertight compartments, tanks, interior volumes, permeability as well as the inflow opening, hatches, cases and watertight doors (Figure 8), a dedicated 1:30 model was manufactured. The model was built in carbon fibre to accommodate the interior volumes correctly, to provide sufficient strength and at the same time keep the mass to a minimum to allow for displacement and stability correcting weights (Figure 9).

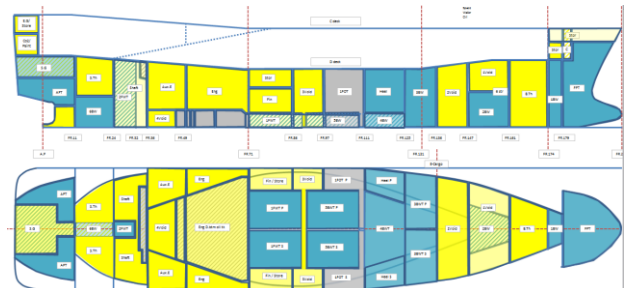


Figure 8: Schematic overview of the watertight division

Since sufficient time stamped images of the actual vessel during flooding and sinking were made from assisting boats and helicopters, the positions and orientations of the vessel during the flooding process were known. This information enabled the execution of captive model tests where the motions of the vessel were forced by means of a 6 degrees of freedom actuator arm called 'hexapod' as shown in Figure 9.

In nature there should be a balance between the water ingress and the position and orientation of the vessel. By measuring the forces imposed by the hexapod on the model to obtain the known track, a check on the volume and speed of water ingress could be made. In this way various flooding openings and progress could be tested. Once the flooding openings were sufficiently accurately established, the same model was used for flooding and sinking tests in free drifting condition.

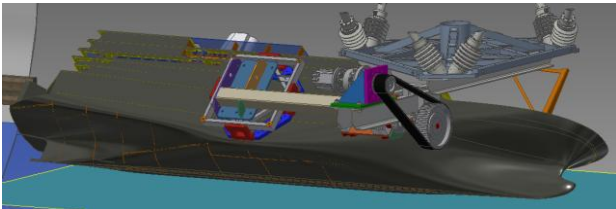


Figure 9: Model and test set up for the captive flooding

To avoid scale effects due to the compression of air inside the model, the tests were conducted in the Depressurised Wave Basin where the air pressure was lowered to 1/30 atmosphere. Free drifting flooding and sinking tests were also conducted in the harbour of the basin as well as in the Shallow Water Basin under atmospheric conditions (Figure 10). In this way the effect of the depressurised environment could be investigated.

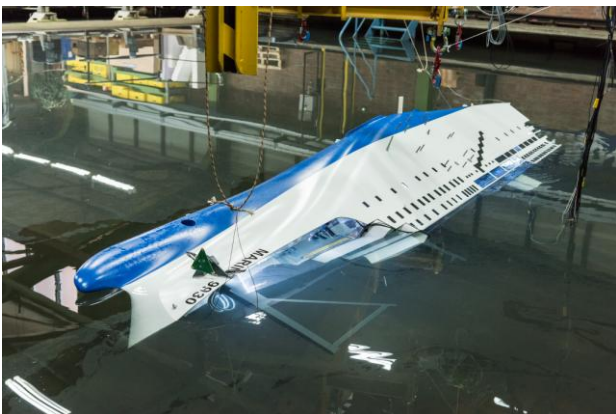


Figure 10: Flooding tests in free drifting condition

The model tests were accompanied by numerical flooding simulations. For this purpose a 3-D geometry model of Sewol was developed and implemented in a numerical flooding simulation model. This computer code was validated against the results of the model tests and then applied to check additional flooding scenarios (Figure 11).

3.2 RESULTS

The flooding investigation focussed on two scenarios: in the ‘C-deck’-scenario, at 45 degrees of heel, water ingresses through the louver vent opening at the C-deck (indicated in Figure 1) and starts to flood this deck. At 48 degrees of heel, the open window at the C-deck increases the inflow of water. Subsequently also the other decks are flooded and the vessel further capsizes and sinks.

In the second scenario, the water flowing in through the C-deck louver vent opening follows the vent casing to the stabiliser room. Subsequently this water flows into the engine room through the watertight door which was not closed at the time. This ‘stabiliser room’- scenario proved less sensitive for small changes in the loading condition and its longitudinal centre of gravity is closer to the specified value.

Therefore it was concluded that the ‘stabiliser room’ scenario is more likely than the ‘C-deck’ scenario.

In contrast with expectations, it was found that the speed of heeling in depressurised environment was slower than in atmospheric condition. The measurements however indicated that the water ingress in the first stage in depressurised condition was faster resulting in a lower centre of gravity and thus less heel.

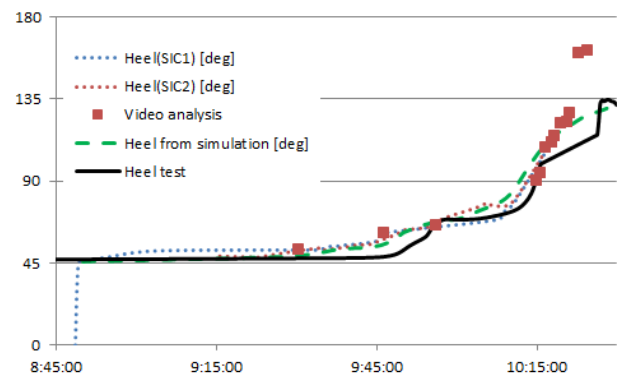


Figure 11: Time traces of heel from simulation compared with model tests and with the stills from video of actual flooding.

4. CONCLUSIONS

Based on the results of the numerical simulations, model tests and nautical simulator runs conducted, the following conclusions have been drawn from this investigation:

- In the investigated loading conditions, the vessel’s turning and heeling are strongly coupled (no heeling without turning, no turning without heeling) and sensitive to stability-level, trim, pre-heeling, forward speed and steering.
- The 3-D geometry of the hull, in particular the slender bow section and the wide aft body as well as the large recess areas for the car ramps at the stern of the vessel, resulted in a degradation of transverse stability of the vessel at heeling angles between 10 and 40 degrees.
- In the tested stability levels (GM = 0.60 m to 0.06 m) the vessel did not comply with the international regulations for passenger vessels (Article 3.1 of the IMO MSC Intact Stability Code 2008).
- At initial stability level GM (0.45 m) in some tests the vessel heeled with more than 18 degrees at a rudder angle of 12 to 15 degrees. Such a heeling

angle is in excess of the heeling angle that can be expected based on international rules.

- Changing the trim from 0.5 m by the stern to 0.5 m by the bow by moving weight horizontally forward, the stability $GM = 0.45$ m changed to $GM = 0.23$ m.
- With the first cargo starting to shift at the threshold angle of 18 degrees, the heel angle increased to 33 degrees, at which other cargo shifted, resulting in a heel angle of 45 degrees.

The excursion of the cargo and the speed of the shifting have effects on the turning and heeling rate but not on the final heel angle achieved.

- In their lashing requirements for roll-on roll-off passenger ferries, international regulations only account for weather and size of the vessel. The present study shows that also in calm seas, the hydrodynamic properties of the vessel can lead to dangerous situations.
- Model tests, simulations and runs on the simulator showed that a combination of low initial transverse stability of the vessel ($GM = 0.1$ to 0.3 m) in combination with 10 degrees SB rudder followed by 25 degrees SB rudder, results in SB turn with a track which resembles the AIS track and a heeling that reached the threshold value of 18 degrees.
- The model tests showed that autopilot steering in combination with active stabilising fins was capable to steer the vessel even with a GM value of only 0.06 m. In the simulator the helmsman was also capable to steer the vessel in this tender condition.
- The application of an external force on the port side stabilizer fin did not significantly affect the turn of the vessel. The highest rate of turn achieved during all model tests (different combinations of winch force, direction and duration) was 2.7 %/s. This maximum value was obtained using a winch force that increased the rate of turn, but decreased the heel angle. So during the model tests no runs resulted in the larger rates of turn provided by the External Force Task Force within SIC based on their analysis of the raw AIS heading data, even when applying a winch force equal to the fin yielding limit.
- The flooding scenario that resembled the actual observed and recorded ship sinking behaviour best, started with water ingress through a louver vent opening just above the C-deck at a vessel heel of approximately 45 degrees. The ventilation casing led the water to the stabilising room. From there through a watertight door, which was not closed, the water flooded the engine room. The draught and heel increased and the C-deck flooded through an open window at 48 degrees heel and through scupper pipes. This resulted in progressive flooding of the C and D-decks and the final stage of capsizing. Finally the vessel sank stern first.
- Flooding model tests and computer simulations have demonstrated that closing all watertight doors and hatches would have resulted in a longer period of floating of the vessel in capsized condition.

Due to the lack of data recorded by SEWOL, the position data received from the AIS transmitter was the main reference for conducting this investigation. AIS is a system for monitoring the steady state condition of a vessel. Due to limitations of sensors, data acquisition, sampling and transmission, it can not be considered accurate to describe the dynamic behaviour of a vessel during fast turning and large heeling such as in the subject case.

Therefore in this investigation the AIS data is mainly used as a reference for the ship's position track. The vessel rate of turn derived from the raw AIS heading data is not considered reliable. A number of parameters and uncertainties involved, such as the current flow, implicate that a perfect correlation between model tests and AIS data cannot be expected.

Since no realistic combination of winch force, direction and duration attained the high rate of turn as derived by the External Force Task Force of SIC from the raw AIS heading, the hypothesis of an external force that caused such high values of rate of turn was rejected.

The investigation results show that a low initial transverse stability of the vessel, in combination with a moderate rudder angle, results in a turn with a track which resembles the AIS track and a heeling that reached the threshold value of 18 degrees at which vehicles at cargo started to shift.

It is noted that in the stability conditions investigated, with GM ranging from 0.60 m to 0.06 m, Sewol did not comply with international regulations IMO MSC Intact Stability Code 2008.

Although no part of this investigation, it is noted that the low level of initial transverse stability of Sewol may have originated from a combination of the following:

- High centre of gravity of the ship in empty condition (light weight ship).
- Cargo weight and location upon departure.
- Lack of ballast water upon departure.
- Consumption of fuel and freshwater, de-ballasting, partially filled tanks (free surfaces) during the first 12 hours of the voyage.
- Trimming the vessel by the bow.

Specific data on the vessel stability, such as the results of the inclination tests after the conversion of the vessel in 2012, have not been provided.

The MARIN Reports describing this investigation and the results in full detail (ref. [1] to [5]), have been released by SIC for public use.

5. FOLLOW UP

This investigation shows that ferries exhibiting large heeling angles in a turn in combination with vehicles and cargos that are not properly secured, can lead to disasters even in calm water conditions. This is especially relevant for ferries and ro-ro-vessels that apply so called 'weather dependent lashing'. The results of this investigation have inspired additional research into the heeling of passenger vessels that do comply with IMO stability regulations during turning. A proposal to improve the international requirements on heeling during turning (Intact Stability Code 2008) is submitted to IMO MSC [6].

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AUTHORS BIOGRAPHY

Henk van den Boom is a naval architect (MSc Delft, 1980) with more than 40 years experience in model testing, numerical simulation, ship trials and offshore monitoring campaigns. For 27 years he was in charge of MARIN's Trials & Monitoring department. As a senior project manager he was leading the SEWOL investigation at MARIN.

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Rinnert van Basten Batenburg (Naval Architect HTS Haarlem in 1998). After 8 years of experience in heavy lift and ship salvage, he is currently working as Senior Project Manager at MARIN's Ships department and conducting seakeeping tests and simulations.

Seo, Seung Taek was in charge of the investigation "Structure and compartment of watertight integrity, verifying flooding simulation and model test" to SEWOL Investigation Commission(SIC). He carries 18 years of balanced job experiences in maritime industries as a classification senior surveyor, design approval engineer, shipyard production manager and investigation officer.