Fatal stability loss of a small craft on a wave crest – based on a real safety investigation

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ABSTRACT

The capsizing of a pilot boat in average weather conditions has generated questions about sufficient stability regulations and uncertainty in pilot boat operations. Abnormal wave formation due to the interaction of a turning vessel and sea surface waves raised particular problems associated with the special operational conditions of the pilot boat. Investigation of the accident has shown that the V-bottom shaped boat may lose 70% of the righting arm maximum on a crest of a typical steep sea surface wave compared to the calm water line situation. This, combined with the external loads and other dynamic effects, caused capsizing of the pilot boat.

Keywords: *pilot boat, V-shaped bottom, boat stability, stability on wave crest.*

1. INTRODUCTION

This paper is based on the investigation of the pilot boat accident which took place in the Gulf of Finland, south of Emäsalo, on 8 December 2017 at approximately 5 PM, Safety Investigation Authority Finland (2018).

Meteorological conditions

Based on the Finnish Meteorological Institute's information the wind in the area was 190°/10…12 m/s with gusts of maximum 15 m/s. The significant wave height was 2 meters. The maximum wave height was 3.8 meters. Waves were coming from 205°. It was dark during the occurrence. The conditions were considered safe for the use of the pilot boat.

Sequence of events leading to the accident

A pilot boat prepared to collect a pilot from a tanker proceeding with the speed of about 9 knots in rough seas in the Gulf of Finland off Emäsalo in December 2017. The pilot boat had followed the tanker *Sten Nordic* at about 20…50 meters from the stern where it was sheltered from the sea waves. The tanker started to prepare for the disembarkment of the pilot by making lee for the operation. When *Sten Nordic* was turning hard to port the pilot boat was to proceed towards the port side of the vessel. The pilot boat was at the distance of 20…30 meters from the stern of the tanker and became exposed unexpectedly to high, steep recurring waves caused by the combined effect of the vessel and the sea waves. The path travelled both by the tanker and that of the pilot boat *L-242* are shown in Figure 1.

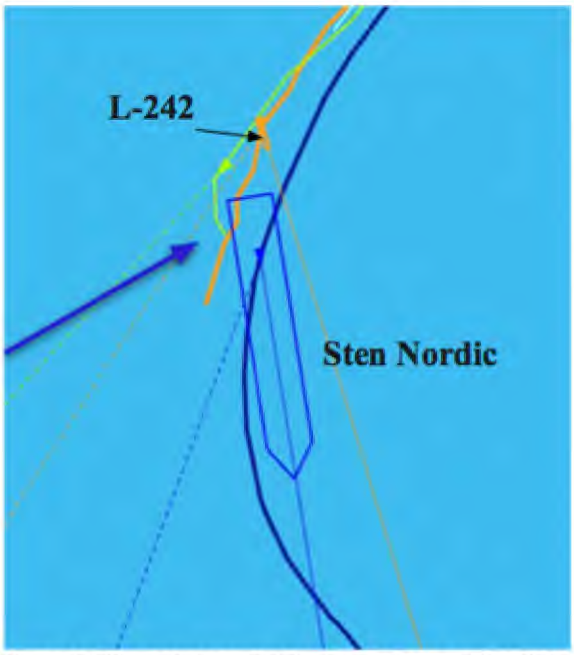

Figure 1: The paths travelled by the tanker and the pilot boat L-242 shortly before the boat capsizing.

The situation prior to the boat capsizing is shown. The blue arrow depicts the prevailing direction of the sea waves' propagation. The speed of the boat was approximately 9 knots.

The stability accident

Suddenly the pilot boat rolled, lost stability and capsized to the port (left) side. After floating for 10 minutes the boat turned upside down.

No signs of the pilot boat's crew were seen during the six hour rescue operation. Eventually the pilot boat sank into the 30 meter deep water. During the inspection dive the crew was found in the cabin wearing survival suits. The Safety Investigation Authority Finland commenced a marine safety investigation in which one of the main safety issues was to find out why the pilot boat lost stability and capsized in prevailing conditions. This issue has wider importance to enhance the general safety of small boats operating in heavy seas.

2. MAIN PARTICULARS AND STABILITY OF THE BOAT

Particulars of the pilot boat

The pilot boat was a high-speed pilot boat of the Kewatec Pilot 1500 type. The boat's LOA was 14.5 meters, breadth 5.1 meters and it was powered by two Scania DI13 Marine Engines of 331 kW (450 hp) connected to two axis driven propellers. The boat had two rudders. The displacement of the boat was 19 m^3 and maximum speed 27 knots.

The hull was divided into five watertight sections below the main deck. The wheelhouse was attached on the deck with vibration damping devices and had only cables running through holes into the hull. The boat was supposed to survive with one watertight section flooded but all the inlets, locks and bulkheads should have been closed. A photograph of the boat is shown in Figure 2.

Figure 2: Pilot boat L-242 investigated after the accident. (Source: SIAF)

The stability of the pilot boat

The risk of the pilot boat capsizing had not been previously identified. The pilot boats were regarded as safe in all conditions and were generally assumed by the crew to be self-righting, due to which the capsizing was a surprise. The users were not sufficiently aware of the boat's stability characteristics in strong waves.

The pilot boat was designed and constructed according to category B requirements of the Finnish Maritime Administration (FMAW, version 2009.1). Finnish VTT Expert Services Oy had inspected the boat based on the Category B requirements and issued an inspection report including the stability information.

The pilot boat was supposed to be capable of operating in conditions where the significant wave height is 4 meters and the maximum wind speed is 21 m/s as well as be to endure a maximum heel of about 75°. The pilot boat had not gone through the inclination test, but the stability information based on the calculated information (presented in Figure 3) was obtained from the previous tests of its sister vessels. The investigation group decided to verify this information.

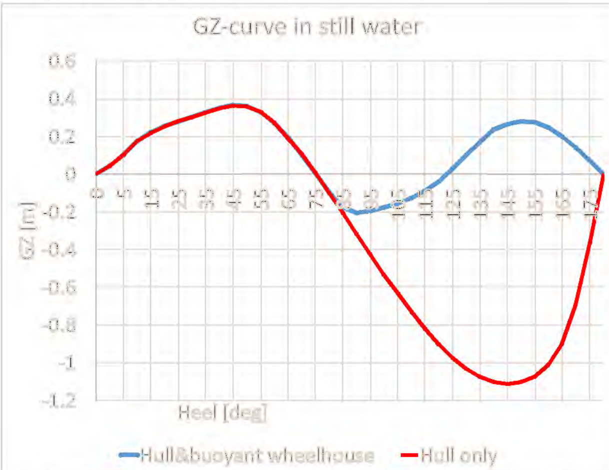

Figure 3: Righting moment curve (*GZ*-curve) of the pilot boat.

The Safety Investigation Authority Finland ordered an inclination test to be carried out for one of the sunken pilot boat's sister vessel in a loading condition much the same as the sunken pilot boat to verify the results of the calculations. This was conducted by Beacon Finland Oy under the supervision of the investigation team. The results of this inclination test were in line with and validated the results of the calculated stability values but did not explain why the pilot boat capsized. The Safety Investigation Authority Finland ordered a simulation from Napa Oy modelling the factors effecting the pilot boat in different wave conditions.

It was observed that the restoring moment of the pilot boat can temporarily lose up to 70% of its maximum in steep waves, during which a sudden, strong external force can capsize the boat. Such an external force can occur due to a rudder movement or a powerful gust of wind. No account of these factors had been taken in the design, manufacture or use of the boat. On the basis of the investigation, there is also reason to believe that the crew of the pilot boat *L-242* had no grounds for believing that the boat would capsize.

Risk management

In the investigation, it emerged also that in Finland no clear official standards exist with regard to commercial craft, which has led to the interpretation and adaptation of a wide range of rules. This creates the risk that insufficient account is taken of special standards applying to various intended uses of commercial craft and the conditions in which they will be used, during the vessels' design and manufacture, and when ensuring their safe use.

The users were not sufficiently aware of the boat's stability characteristics in strong waves. The orientation of pilot boat operators varies and is not necessarily sufficient in terms of the challenging nature of the work or ensuring safety. Risk identification and safe practices are largely based on "silent" knowledge rather than documentation and systematic risk assessment.

3. THE WAVES ENCOUNTED BY THE BOAT

Wave conditions, at the time of accident, were typical for the Gulf of Finland at this time of a year and characterized by two-directional wave propagation and a double-peaked wave spectrum. The significant wave height was H_S= 2 m and the zero-crossing period T_Z=4.7 s. Waves of length 50 m to 150 m propagated in the 240° direction while the direction of shorter waves was directly from the south.

The initial heading of the tanker was 240° and thus it provided a good shelter for the pilot boat. Turning of *Sten Nordic* to port exposed the pilot boat to the sea waves (refer to Figure 1). Moreover, interaction of sea waves with the tanker hull resulted in formation of steep waves that were sweeping along the hull downstream astern to the region where the pilot boat was located. These waves, interacting with the open sea waves, were encountered by the pilot boat.

Qualitatively the formation of steep and breaking waves downstream of a turning ship due to interaction of the turning vessel and the sea waves can be explained by the observations made during earlier tests conducted in the multi-functional model basin of Aalto University. Turning circle tests were conducted in irregular long-crested waves. The primary goal of the tests was to reveal roll resonance motion of a RoPax in stern quartering seas (Acanfora & Matusiak, 2016). A still photo capture of the video taken during the tests is shown in Figure 4.

Figure 4: Model of a RoPax vessel in long-crested irregular waves in the multi-functional basin of Aalto University.

The waves used in the model tests were higher and longer (H_S= 4.8 m and T_1=5.9 s) than the ones that were present during the accident. However, a similar effect on the waves formed downstream due to turning of *Sten Nordic* can be expected.

4. QUASI-STATIC ANALYSIS OF THE BOAT STABILITY

A thorough and reliable dynamic analysis of the pilot boat behavior and capsizing in such a complex wave environment proved to be impossible. There are several reasons for this. The V-shaped, shallow draft hull of the boat differs much from the displacement ship hull forms. Large and slow variations of the wetted surface in waves contradict the linearity assumptions of the radiation and diffraction forces of traditional seakeeping methods and also of so-called hybrid models. Thus, the available tools used in analyzing vessel motions in waves, proved to be insufficient.

Assumptions of the quasi-static approach

The relatively low speed and the heading of the boat, combined with waves much longer than the boat length, resulted in a period of encounter higher than the roll resonance period (approx. 2.4 s). This made a quasi-static analysis of the boat floatation and stability feasible and relevant for the investigation of accident. The assumption is that the boat follows well the waves and its position is governed by the weight and the hydrostatic pressure. The latter takes the wave profile into account. Large variations of the wetted surface result in drastic and highly non-linear variations of the restoring moment given in the form of a *GZ*-curve. The dynamic effects related to the boat motion, such as inertia, radiation and diffraction forces, are disregarded. The effect of forward speed (approximately 9 knots in this case) on dynamic pressure and wave-making are disregarded as well.

Tool used in evaluation of stability change in waves

The tool for evaluation pure loss of stability on a wave crest, being a part of the second-generation intact stability ship criteria (Tompuri et al, 2017), was used. Calculations were conducted with the NAPA software.

Sinusoidal deep-water waves of lengths (λ) from 40 m to 150 m and heights (H) from 1.5 m to 4.5 m were used. Wave heights were limited by the wave breaking criterion $H/\lambda<0.1$. The considered heading angles were from 20° to 60° with head waves corresponding to zero heading. For each heading and wave case, the boat was set in a wave at different positions and the one with the minimum stability was selected as a reference. For each case the static equilibrium position of the boat and it's *GZ*-curve were evaluated. An example of the static equilibrium position of the boat, with substantially weakened stability, in a regular wave is shown in Figure 5.

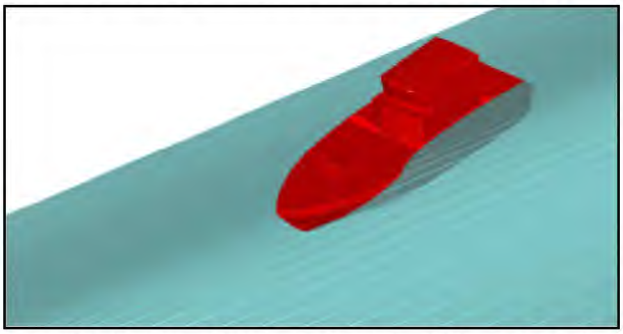

Figure 5: Position of static equilibrium of the pilot boat in regular sinusoidal wave of length 40 m and height 3 m. Heading 50°.

The knowledge of the *GZ*-curve in different situations made it possible to evaluate the boat response to both static and dynamic external loads.

External loading

Apart from possible dynamic effects related to boat motion, the most relevant external loading was caused by the rudders. The rudders of the capsized boat were turned 40° to port. The heeling moment M_{ext} caused by turning both rudders by 40° was evaluated using the methodology of Molland (2007) and resulted in the lever of external loading

$$l_{ext} = M_{ext} / \Delta = 0.0834 \text{ m}, \qquad (1)$$

where Δ is buoyancy.

Two types of rudder loading on the boat were considered, namely the static one and the dynamic one given as a step function. The latter is treated in a similar manner as the wind gust loading of the weather criteria, i.e. knowing the *GZ*-curve and the arm of the dynamic loading the areas made-up by both are compared. If the work done by the external loading exceeds the work done by the restoring moment the vessel capsizes. This is illustrated in Figure 8 in the following paragraph.

Results of the analysis

For the static loading, the cases with the external loading exceeding the maxima of the *GZ*-curves were identified, that is

$$l_{ext} > GZ_{MAX} \;. \qquad (2)$$

The results of this static, i.e. slowly increasing, loading by rudders on the boat in the critical waves are presented in Figure 6.

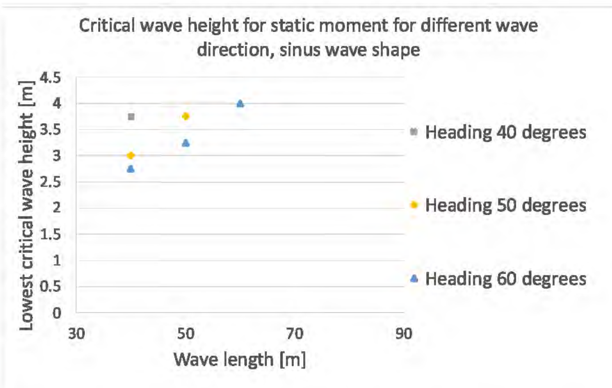

Figure 6: Critical wave heights for static loading caused by turning rudders by 40°.

In Figure 7 the critical waves and headings for rapid (step function form) rudder load are presented.

An example of the boat capsizing due to a rapidly changed rudder angle in the critical wave and heading condition is illustrated in Figure 8. The static balance of the boat in this condition yields a heel of 24°.

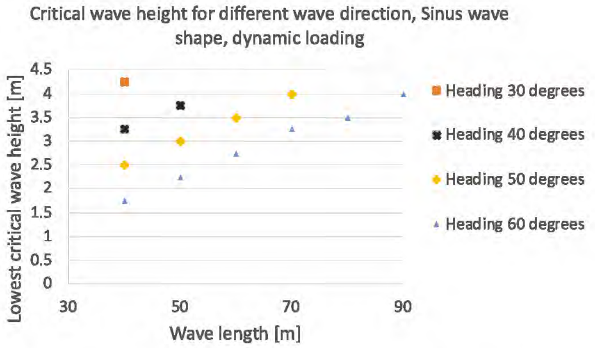

Figure 7: Critical wave heights for dynamic (step function) loading caused by turning rudders by 40°.

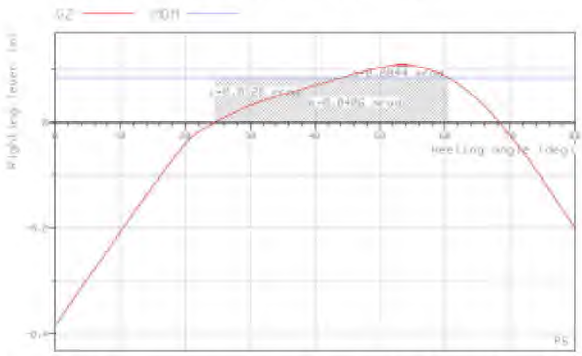

Figure 8: Dynamic loading due to rapidly turned rudders capsizes the boat in 40 m long and 3.5 m high wave, heading 40°.

A substantial decrease of the GZ-curve maximum, stability range and the capability to withstand dynamic loads is noted. The latter is not enough to resist dynamic load of the rudders.

It is clearly seen that the dynamic rudder command substantially increases the risk of capsizing. A nearly linear increase of critical wave height with length suggests that wave steepness is the primary reason for capsizing. The critical wave steepness depends upon heading. The most dangerous heading capsizing the boat in waves of smallest steepness is 60^0.

Static and step function type loading approximations are idealized realizations of the rudder action. It is impossible to find out what was the actual rudder command prior to capsizing. Most likely the loading caused by them was something in between.

5. CONCLUSIONS

Qualitatively, the conducted quasi-steady analysis of the boat's behavior in waves taking into account the effect of rudder heeling moment agrees with the observations and testimonies in the conducted investigation. In the actual critical situation, which in this case led to the accident, the pilot boat was subjected most likely to steep and breaking waves. Because the environment of such waves is difficult to evaluate and to reconstruct a simple regular wave model was used to demonstrate the effect of surface waves on the boat's stability.

The conducted investigation clearly shows that the restoring moment drops rapidly when the boat is affected by steep waves. In particular, relatively long, beam-quartering waves may be dangerous.

Evaluating the semi-displacement pilot boat stability solely on the basis of GZ-curve in still water seems not to be sufficient. The logical development of stability criteria for this type of boat, often operating in harsh weather conditions, would be checking the boat's stability in waves, as presented in the paper. Actually, such a check is a part of the second-generation of intact ship stability criteria.

The only difference between the pure loss of ship stability on a wave crest check and checking the stability of a boat in waves is the range of headings. The ship criteria consider stern and stern quartering waves of a length close to the ship length, while in case of a boat the range of headings should be larger and the considered waves longer.

To improve maritime safety in the use of the similar type craft as the capsized pilot boat, the Safety Investigation Authority Finland (SIAF) recommends that the regulatory authority should draw up regulations for special-purpose craft. The regulations should take into account the various purposes for which the craft is designed as well as the special requirements related to the conditions in which the craft is used.

The Safety Investigation Authority also pointed out that the owners should improve the orientation processes and professional competencies of the craft users in such a manner, so that the seaworthiness and safe handling of different types of craft can be guaranteed in all operating conditions.

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