Model Experiment on Pure Loss of Stability for a Ship in Astern Waves and Its Relationship with the Second Generation Intact Stability Criteria

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ABSTRACT

For examing the applicability of direct stability assessment for pure loss of stability in astern waves to the accident due to the relevant failure mode, a model experiment for an ocean research vessel which has a hull form similar to the accident vessel was executed and then its results are compared with the numerical simulation using a coupled surge-sway-roll-yaw model. As a result, it was confirmed that the numerical simulation to be used for direct assessment qualitatively and quantitatively explains the experimental results. This good agreement suggests that the applicable speed limit for the draft criteria is reasonable and the deck space surrounded bulwark should be regarded as water-tight for the numerical simulation.

Keywords: *direct stability assessment, bulwark, ocean research vessel.*

1. INTRODUCTION

The second generation intact stability criteria, which are now under development at the International Maritime Organization (IMO), will include explicit design requirements for preventing stability failures due to restoring variation in waves for the first time at the IMO. This could be useful for designers to avoid possible capsizing accident. To demonstrate such benefit for ship designers, at least it should be examined whether the new requirement could prevnt major capsizing accidents in the past.

In 1980's an ocean research vessel was lost off Fukushima in Japan when she ran in heavy astern seas. This accident was widely reported in media with the term "broaching". The accident investigation finally suggests that this accident was triggered with loss of restoring moment in stern quartering waves (The Japan Association of Marine Safety, 1990). Thus it is important whether the draft stability criteria for pure loss of stability in following waves to be included in the second generation intact stability criteria can explain this accident or not.

It is known that the restoring moment is likely to change when the wavelength is nearly equal to the ship length. When the midship of a ship is located at a wave crest, the roll restoring moment could reduce or nearly become zero and as a result, capsizing could be occurred sometimes. Paulling (Oakley et al., 1974) named this kind of capsizing mode as "pure loss of stability" and defined as "A ship encounters one or more very steep high waves, with little or no preliminary rolling motion, simply loses all stability when a crest moves into the amidships position and 'flops' over".

The new intact stability criteria of pure loss of stability are composed of the two-layered vulnerability criteria and the direct stability assessment procedure. Here the direct stability assessment procedure is most accurate and normally relys on numerical simulation in the time domain, which should be validated with model experiment. Once this direct stability asessmentprocedure is established, the vulnerability criteria can be easily developed as a simplified version of the direct assessment.

As one of the numerial simulation tools to be used for the direct assessment for pure loss of stability, a surge-sway-yaw-roll (4DoF) simulation model was proposed by Kubo et al. (2012) and validated with free running model experiment of the C11 class containership. However, the containership accidents due to pure loss of stability are not so well known so that we conducted free running experiment using the model of a ship which is similar to the lost ocean research vessel and then compared the results with the numerical simulation of the 4DoF model. This comparison could facilitate our discussion on the criteria for pure loss of stability.

2. ACCIDENT IN ASTERN SEAS

In June 1986, a research ship sunk off Fukushima in Japan on its maiden voyage without any emergency call. The maritime court concluded that the height of centre of gravity was increased due to several changes of design during construction and then during her maiden voyage the ship heeled significantly when she ran in severe stern quartering waves. The principal particulars of the ship at the initial design stage and the estimated condition at the accident are shown in Tables 1 and 2, respectively.

Table 1: Principal particular of the accident ship in the initial design phase.

Items	Ship
Length(PP)	22.00m
Breadth	5.00m
Depth	2.20m
Mean draught	1.75m
GM	0.56m

Table 2: Condition when the accident occurred

Ship speed	10[kts]
Wave height	3.0[m]
Wave period	5~6[s]
Encounter angle	-45[degrees]
GM	0.41[m]

In this study, we used a ship having a relatively similar hull form in the literature (Small Ship R&D committee, 1988) for the model experiment. The standard condition for the experiment was the Froude number, *Fn*, of 0.35, the wave steepness, H/λ, of 1/13, the wavelength to ship length ratio, λ/L_{pp}, were 1.75, and the encounter heading angle, χ, were -30 degrees from the wave direction. These are selected to be close to the accident condition except for the heading angle, which is slightly smaller because of the width of the used model basin.

3. MODEL EXPERIMENT

The free running model experiment was carried out at a seakeeping and manoeuvring basin of the National Reserch Institute of Fisheries Engineering, which is 60 m long, 25 m wide and 3.2 m deep. A 1/10 scaled model was used; its principal dimensions and model photo are shown in Table 3 and Figure 1, respectively. In this experiment, two different metacentric heights, GMs, were used: GM of 0.041 m simulates the accident, and that of 0.056m was based on the initial design. The model has a extended low weather deck which are surrounded by bulwark with freeing ports.

Table 3: Principal particulars of the ship model

Items	Ship	Model
Length(PP)	22.00m	2.20m
Breadth	4.90m	0.49m
Depth	2.20m	0.22m
Mean draught	1.75m	0.175m
Block coefficient	0.61	0.61
Metacentric height	0.41m 0.56m	0.041m 0.056m

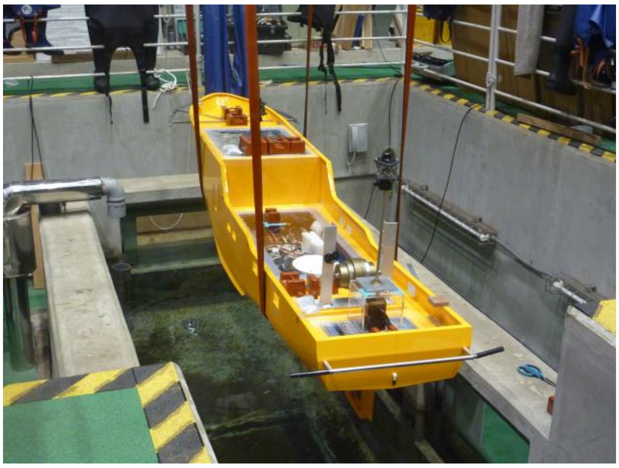

Figure 1: Photo of the ship model

Table 4: Experimental condition

Froude number	0.15,0.20,0.25,0.30,0.35,0.385,0.40
Wave steepness	0.025,0.04,0.05,0.06,1/13,0.1
The wave length to ship length ratio	0.80,1.0,1.25,1.5,1.75,2.0
Encounter angle	-5,-15,-30,-45
Rudder gain	0.5,1,2,3

The ship model ran in regular stern qusartering waves with a proportional autopilot for keeping a mean heading angle from the wave direction and with a constant propeller revolution. The roll, pitch and yaw angle were measured by an optical fibre gyroscope inside the ship model, and the ship position was detected by a total station system, which consists of a theodorite and a prism. The experimental conditions are shown in Table 4, and were based on the standard one and those for identifying sensitivities of the operational parameters.

The experimental procedure was basded on the ITTC recommenbded procedures for intact stability model tests, 7.5-02-07-04.1. First the model was situated near the wave maker. After the wave train propagates enough in the model basin, the model propeller revolution was increased to the specified value to achieve the required speed and the steering system activated.

4. RESULT OF MODEL EXPERIMANT

Examples of time histories measured in the experiment with the accident and designed GM are shown in Figure 2 and Figure 3, respectively. Here the term "wave height" in these gragh represents the wave displacement at midship, which is defined downward positive. The roll and yaw angles are defined starboard positive. The examples indicate that the ship significantly rolls to the starboard direction whenever the ship centre meets a wave crest. This can be regarded as typical pure loss of stability mode. Larger roll angle can be found in case of the accident GM.

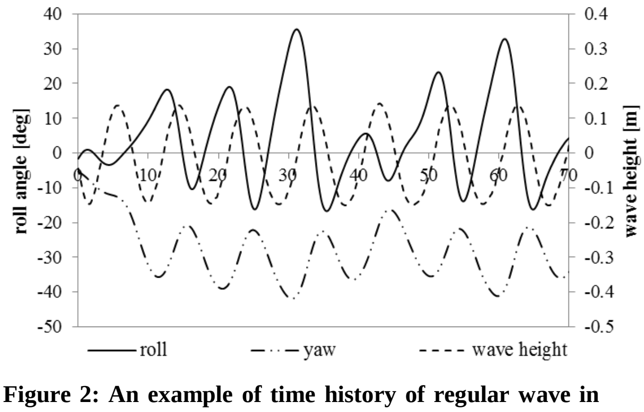

Figure 2: An example of time history of regular wave in GM=0.41m (F_n=0.35, H/ λ =1/13, λ /L=1.75, K_p=1.0, χ =-30[deg])

The effects of several parameters on the maximum roll angle, based on the free running model experiment, are shown in Figures. 4-8. The maximum roll angle increases with the ship forward speed and the wave steepness, as shown in Figures 4-5. In particular, the significant increase of the roll angle can be found when the Froude number is above 0.3. This measured tendency supports the draft vulnerability criteria, which are designed to be applied only the Froude number of 0.24 or over. It is also noteworthy the roll angle is not proportional to the wave steepness so that the phenomenon is nonlinear. The maximum roll angle has a peak at the wavelength to ship length ratio of 1.25 or 1.5 and at the heading angle of -30 degrees. The effect of the rudder gain is not significant so that the operational effect could be limited for this mode.

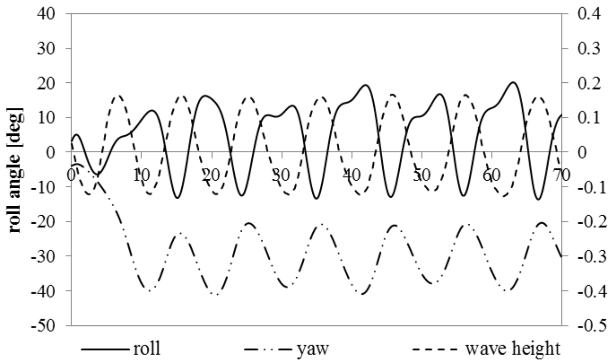

Figure 3: An example of time history of regular wave in GM=0.56m (F_n=0.35, H/λ=1/13, λ/L=1.75, K_p=1.0, χ=-30[deg])

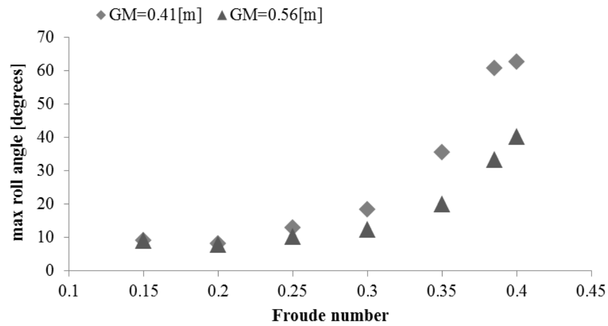

Figure 4: Effect of the Froude number on the maximum roll angle with H/ λ =1/13, λ /L=1.75, K_p=1.0, χ =-30[degrees]

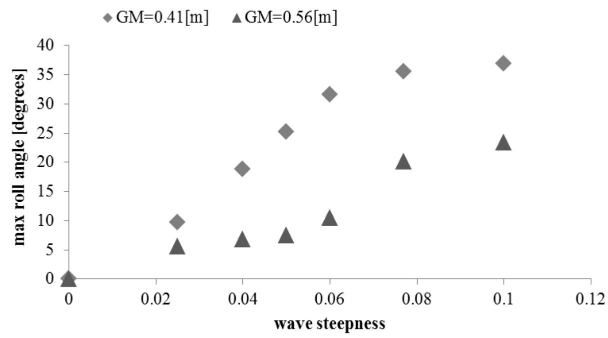

Figure 5: Effect of the wave steepness on the maximum roll angle with F_n=0.35, λ /L=1.75, K_p=1.0 and χ =-30[degrees]

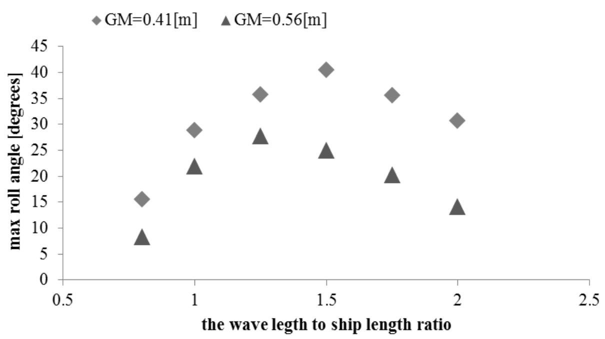

Figure 6: Effect of the wavelength on the maximum roll angle with F_n=0.35, H/λ=1/13, K_p=1.0 and χ=-30[degrees]

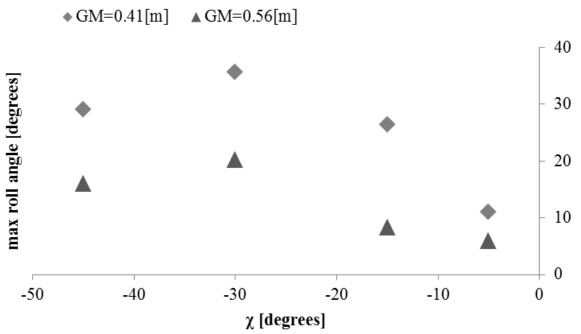

Figure 7: Effect of the heading angle on the maximum roll angle with F_n=0.35, H/λ=1/13, λ/L=1.75 and K_p=1.0

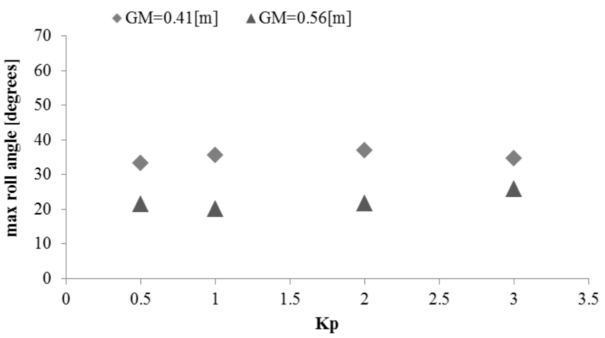

Figure 8: Effect of the rudder gain on the maximum roll angle with F_n=0.35, H/λ=1/13, λ/L=1.75 and χ=-30[degrees]

5. COMPARION WITH NUMERICAL SIMULATION

As a next step, the numerical simulation using a coupled surge-sway-yaw-roll model developed by Kubo et al. were executed and compare its results with the model experiment mentioned above. This model is based on a manoeuvring simulation model with wave-induced forces and moments estimated with a slender body theory under the low encounter frequency assumption (Umeda et al., 1995) as well as the restoring variation under the Froude-Krylov assumption. For calculating the restoring moment, the hull is water-tight up to the level of bulwark top. The calculated righting arms are shown in Figure 9. The roll damping moment was estimated with the roll decay test data as shown in Figure 10. The hull manoeuvring coefficients used here are from the measured ones for the offshore supply vessel model and the rudder parameters are estimated empirically.

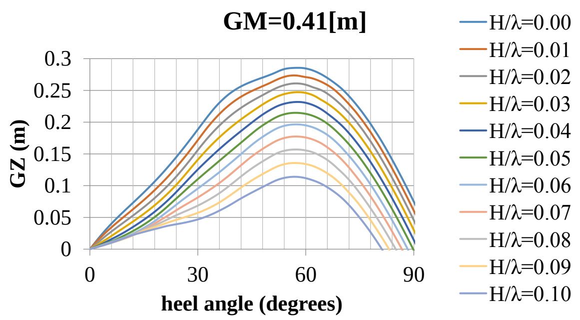

Figure 9: GZ curves used for numerical simulation in longitudinal waves with the wave steepness ranging 0 to 0.1 and the wavelength to ship length ratio of 1 at the wave crest amidship.

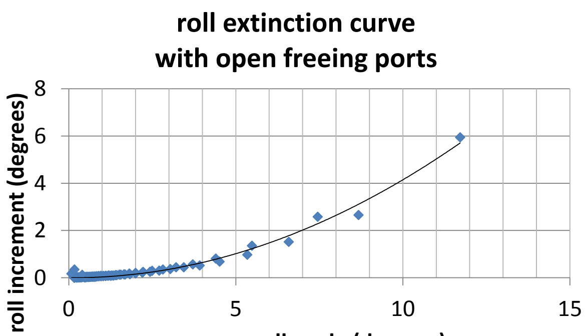

Figure 10: Roll extinction curve of roll decay tests with open freeing port.

As shown in Figures 11-12, the numerical simulation well explains the qualitative difference between two different GMs. In case of the design GM the roll motion includes superharmonics but in the accident GM does not so. For the maximum and minimum values of the roll angle, quantitative agreement between the numerical simulation and the model experiment can be found. However, if we calculated the restoring moment up to the weather deck, the ship in the numerical simulation frequently results in capsizing. This suggests that the bulwark is effective to prevent water ingress above the weather deck at least for short duration when the water level exceeds the weather deck but is still below the bulwark. This could be a clue for developing reasonable vulnerability criteria.

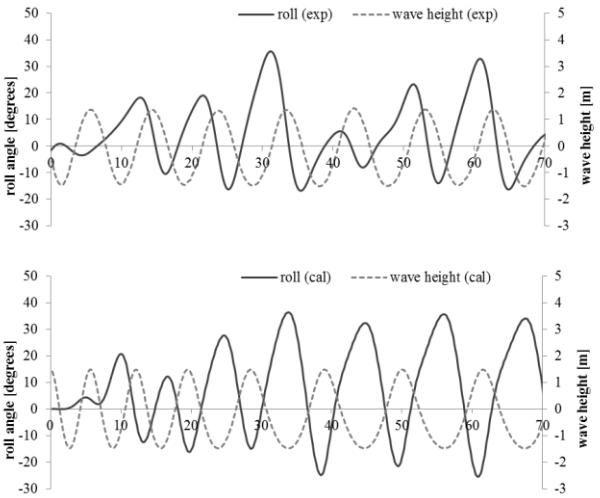

Figure 11: Comparison of ship motions between the experiment and the simulation in GM=0.41m with F_n=0.35, H/ λ =1/13, λ /L=1.75, K_p=1.0 and χ =-30[degrees]

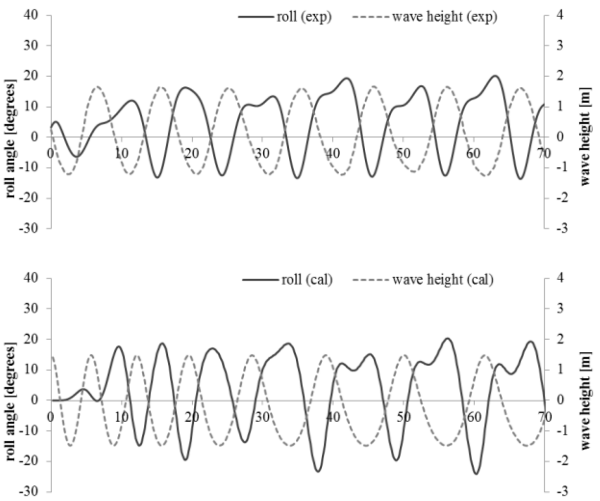

Figure 12: Comparison of ship motions between the experiment and the simulation in GM=0.56m with Fn=0.35, H/λ=1/13, λ/L=1.75, Kp=1.0 and χ=-30[degrees]

Wider comparisons between the numerical simulation and the model experiment for several operational parameters are shown in Figures 13-18. The agreement between the two is generally satisfactory except for the low speed cases and extremely high wave steepness cases. Since low speed case results in relatively high encounter frequency, the wave making and inertia effects could not be neglected so that the simulation model based on high frequency assumption should be applied as well in future.

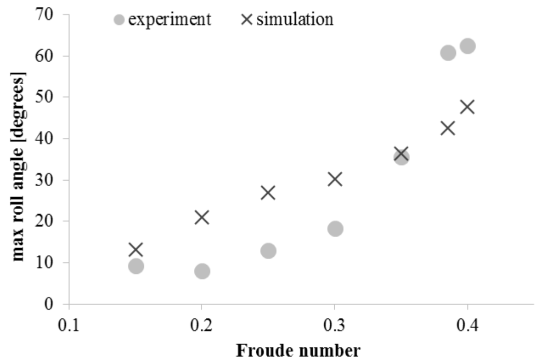

Figure 13: Comparison of the roll angle as a function of the Froude number between the experiment and the simulation with GM=0.41m, F_n=0.15~0.4, H/ λ =1/13, λ /L=1.75, K_p=1.0 and χ =-30[degrees]

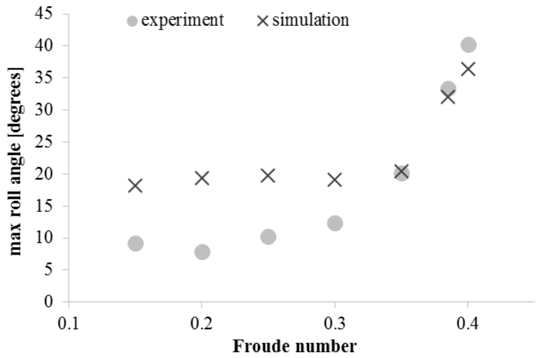

Figure 14: Comparison of the roll angle as a function of the Froude number between the experiment and the simulation with GM=0.56m, F_n=0.15~0.4, H/ λ =1/13, λ /L=1.75, K_p=1.0 and χ =-30[degrees]

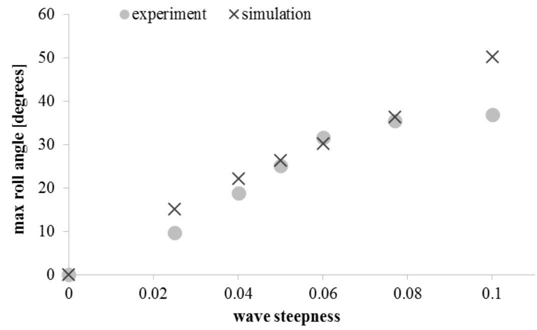

Figure 15: Comparison of the roll angle as a function of the wave steepness between the experiment and the simulation with GM=0.41m, F_n=0.35, H/ λ =0.025~0.1, λ /L=1.75, K_p=1.0 and χ =-30[degrees]

6. CONCLUSIONS

The manoeuvring-based surge-sway-yaw-roll simulation model shows qualitative and quantitative agreements with the free-running model experiment in which significant roll were observed whenever the centre of the ocean research vessel model running in stern quarteriung waves meets a wave crest.

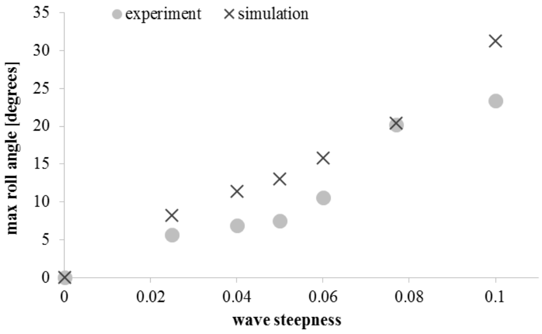

Figure 16: Comparison of roll angle as a function of the wave steepness between the experiment and the simulation with GM=0.56m, F_n=0.35, H/λ =0.025~0.1, λ /L=1.75, K_p=1.0 and χ =-30[degrees]

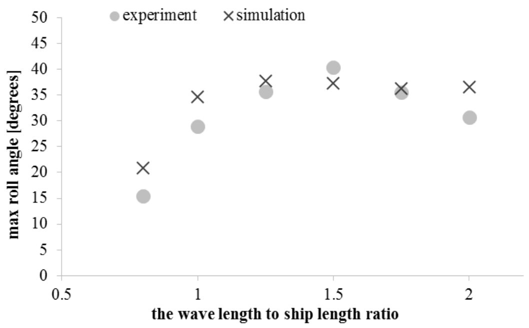

Figure 17: Comparison of roll angle as a function of the wavelength between the experiment and the simulation with GM=0.41m, F_n=0.35, H/ λ =1/13, λ /L=0.8~2.0, K_p=1.0 and χ =-30[degrees]

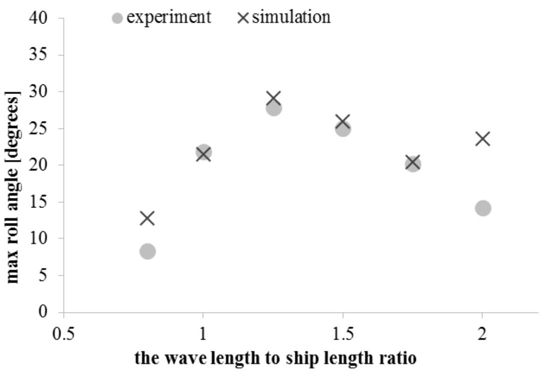

Figure 18: Comparison of roll angle as a function of the wavelength between the experiment and the simulation with GM=0.56m, F_n=0.35, H/ λ =1/13, λ /L=0.8~2.0, K_p=1.0 and χ =-30[degrees]

This suggests that :

1. such numerical tool as a possible direct stability assessment procedure tool well explains the known accident due to pure loss of stability in stern quartering waves;

2. danger of pure loss of stability drastically increases when the Froude number is 0.3 or over.

3. the volume surrounded with the bulwark could be regared as water-tight because of limited time duration.

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