COMPARATIVE ANALYSIS OF RO-RO PONTOON STABILITY: REAL STRUCTURE VERSUS SCALE MODEL

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Abstract: *This paper presents a comparative stability assessment of a Ro-Ro pontoon at full scale and at a 1:25 physical model scale. Inclining tests were carried out on both the real pontoon and the scale model, using systematic weight shifts between port and starboard to determine the metacentric height and righting lever characteristics. In addition, hydrostatic and stability parameters of the real pontoon were calculated with the NAPA software package, which provided equilibrium conditions and righting lever curves in accordance with established stability procedures. The experimental and computational results showed that the scale model reproduced the overall stability characteristics observed in the real pontoon, while numerical values differed as expected due to scaling effects. These findings confirm the usefulness of physical modeling and computational analysis as complementary approaches to the validation of hydrostatic stability in floating structures.*

Keywords: *Stability analysis, NAPA software, Ro-Ro pontoon, Scale modeling.*

1. Introduction

Ro-Ro pontoons play a critical role in facilitating the embarkation and disembarkation of vehicles, and their safe operation strongly depends on hydrostatic stability. Stability analysis is therefore a fundamental requirement in both design and operational phases, ensuring that floating structures can withstand a wide range of loading and environmental conditions. While numerical tools such as NAPA [NAPA,1989] provide accurate hydrostatic and stability predictions, physical scale modeling remains a valuable complementary approach for understanding practical behavior and validating computational results. In this study, the scale model of the pontoon was produced using 3D printing technology based on Fused Deposition Modeling (FDM) [Alperen,2021], enabling a cost-effective and rapid fabrication of a functional prototype. The present research investigates the stability of a Ro-Ro pontoon through a comparative analysis between the real structure and its 1:25 3D-printed model, using both inclining tests and hydrostatic calculations.

2. Inclining Test Methodology

To determine the hydrostatic stability and the position of the center of gravity for both the full-scale pontoon and the 1:25 scale model, the same experimental procedure was applied, based on the inclining test method. This method is defined by the technical document MT.RNR-NT 2/11-99, which specifies the arrangement and shifting of weights to measure heel angles under controlled conditions [Registrul Naval Român (RNR),1999].

The test consists in generating heeling moments by systematically shifting weights from one side of the floating structure to the other while recording the resulting heel angles. From the relationship between the applied moment and the measured heel, the metacentric height (GM) is calculated, which represents a key indicator of the vessel’s initial stability.

During the test, four individual movable weights were used, numbered from 1 to 4 and symmetrically arranged on both sides of the pontoon (port and starboard). Each weight was shifted successively according to the stages shown in Table 1, in order to generate a controlled sequence of heeling moments. The numerical values in the table indicate the active weights at each measurement stage, while the arrows (↑ and ↓) show the direction of the last movement, from port to starboard or vice versa. The abbreviations PS and SB are used in the table to denote Port Side and Starboard Side, respectively. This procedure ensures a symmetrical distribution of moments and provides a sufficient number of independent measurements for the accurate determination of the transverse metacentric height (GM).

Table 1: *Weight shifting procedure applied during the inclining test*

	The variant with ballast consisting of four movable weights		
Ship's side	0	I	II
PS → SB	2 4 1 3	1 2 4 ↑ 3	1 2 3 4 ↑
Ship's side	III	IV	V
PS → SB	1 3 4 ↓ 2	1 3 ↓ 2 4	3 ↓ 1 2 4
Ship's side	VI	VII	VIII
PS → SB	↓ 1 2 3 4	2 ↑ 1 3 4	2 4 ↑ 1 3

The sequence of weight movements followed the stages 0–VIII, covering a complete measurement cycle and ensuring a symmetrical distribution of heeling moments. In each stage, the combinations of weights were selected to produce an ordered progression of applied moments, increasing and then decreasing in amplitude.

The weights were carefully handled, and after each movement the corresponding heel angle was recorded using a digital inclinometer for the full-scale pontoon and a smartphone inclinometer application for the scale model.

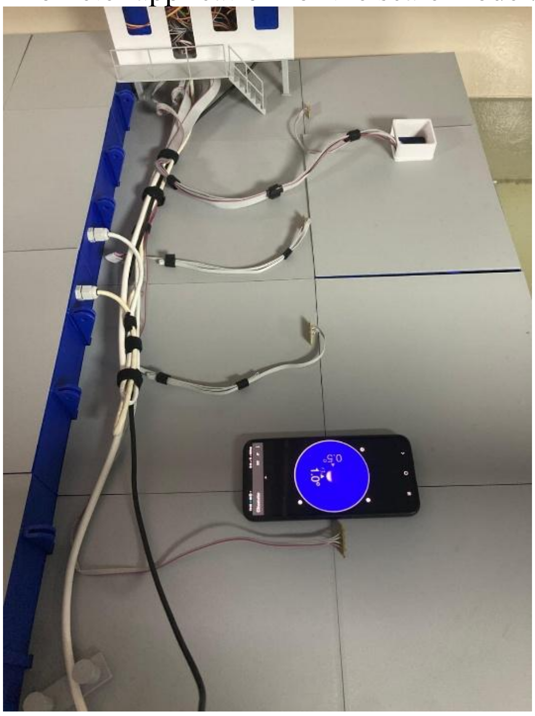


Figure 1: *Measurement of the heel angle on the 1:25 scale model using a smartphone inclinometer application during the inclining test*

The experimental data were subsequently entered and correlated within the NAPA software, where they were used to compute the metacentric height (GM), the vertical center of gravity (KG), and the total weight in the lightship condition. Integrating the measured values into the NAPA environment allowed for the validation of results by comparing the experimental measurements with the numerical hydrostatic analysis, confirming the consistency between theoretical and practical stability evaluations.

The same procedure was applied for both the real and scaled models, with mass and distance values adapted according to the 1:25 geometric scale. This ensures consistency and allows direct comparison between the experimental results of the model and the real pontoon.

A total of at least eight independent measurements were obtained, from which the moment heel curve was plotted and the transverse metacentric height (GM) was determined with satisfactory accuracy.

3. Stability of the Full-Scale Pontoon

The hydrostatic stability of the full-scale Ro-Ro pontoon was evaluated through a combination of numerical simulations and experimental testing. Using the NAPA software package, intact stability calculations were carried out under the lightship condition, providing hydrostatic parameters, righting lever (GZ) curves and compliance with established stability criteria. The numerical results indicated a typical righting lever curve with maximum values reached at moderate heel angles, satisfying the intact stability requirements.

The general arrangement of the full-scale Ro-Ro pontoon in lightship condition is presented in Figure 2, showing the top and side views of the structure. This arrangement illustrates the distribution of compartments and hydrostatic form used in the stability calculations.

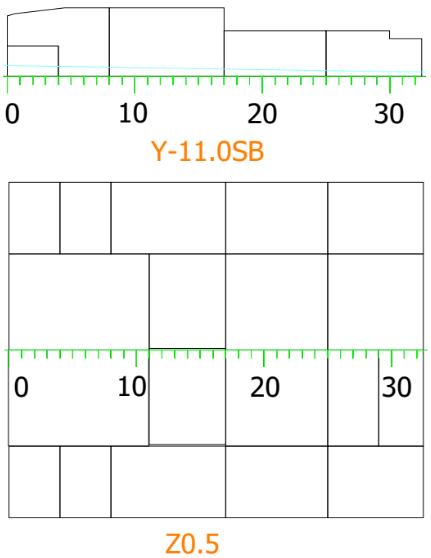


Figure 2: *Top and side view of the full-scale Ro-Ro pontoon (lightship condition)*

In addition to the numerical assessment, an inclining test was conducted on the pontoon in its operational environment. Weights were systematically shifted between the port and starboard sides in order to generate measurable heel angles, from which the metacentric height (GM) was determined. The test procedure was performed according to standard guidelines for stability verification of floating structures. The combination of NAPA analysis and inclining test results provided a reliable reference framework for subsequent comparison with the scale model stability assessment.

Figure 3: *Full-scale Ro-Ro pontoon with Ro-Ro vessel moored alongside*

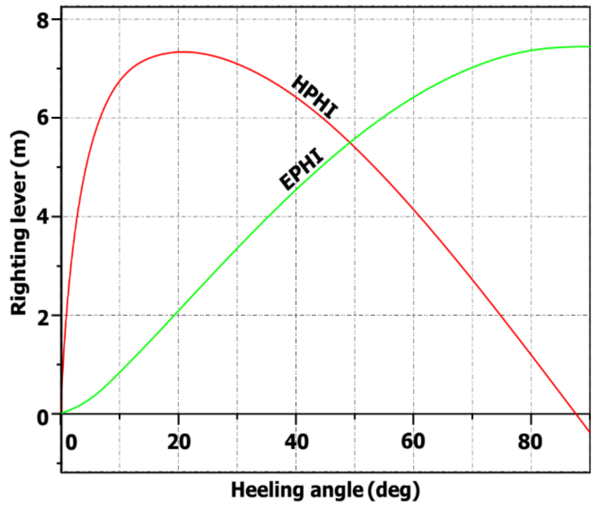


Figure 4: *Righting lever (GZ) curve of the full-scale Ro-Ro pontoon in lightship condition*

The stability curves presented in Figure 4 include both the righting lever (HPHI) and the cumulative area under the curve (EPHI), as functions of heel angle. HPHI represents the conventional righting lever (GZ) curve, expressed in meters, describing the variation of the restoring moment arm of the vessel with respect to heel angle [Morrison,2024]. EPHI represents the integral of the GZ curve, expressed in m·rad, indicating the accumulated area under the HPHI curve and reflecting the total stability reserves available up to a given angle [Henning,2015].

The assessment according to the International Code on Intact Stability confirms compliance with the minimum stability criteria. Specifically:

- Up to 30°, the EPHI reaches 3.355 m·rad, significantly above the minimum requirement of 0.055 m·rad,
- Up to 40°, the cumulative area increases to 4.540 m·rad, exceeding the 0.09 m·rad threshold by a large margin,
- Between 30° and 40°, the incremental area is approximately 1.185 m·rad, well above the 0.03 m·rad requirement,
- The righting lever (HPHI) attains a maximum of about 7.33 m at 20° of heel,
- The GZ value at 30°, corresponding to an HPHI of 7.09 m, confirms a robust righting moment far exceeding the minimum of 0.20 m.

The only notable difference is that the maximum righting lever occurs at an angle of approximately 20°, slightly below the recommended 25°.

This behavior is typical for pontoon-type structures and does not affect the overall conclusion that the intact stability of the pontoon is ensured with substantial safety margins. [International Maritime Organization (IMO),2008].

4. Stability of the Scale Model

The stability of the 1:25 scale model of the Ro-Ro pontoon was assessed through both experimental testing and numerical analysis. The model was manufactured using 3D printing technology based on Fused Deposition Modeling (FDM), which allowed the rapid and cost-effective fabrication of a functional prototype suitable for hydrostatic testing [Halus,2025].

The top and side views of the 1:25 scale pontoon model are presented in Figure 5, illustrating the overall arrangement and geometry of the 3D-printed prototype. This representation highlights the structural fidelity of the model with respect to the full-scale pontoon and provided the basis for subsequent stability testing.

An inclining test was carried out on the model under controlled conditions, following the same procedure applied to the full-scale pontoon. Weights were systematically shifted from port to starboard to induce measurable heel angles, from which the metacentric height (GM) was derived. The inclining test provided direct insight into the hydrostatic response of the scale model.

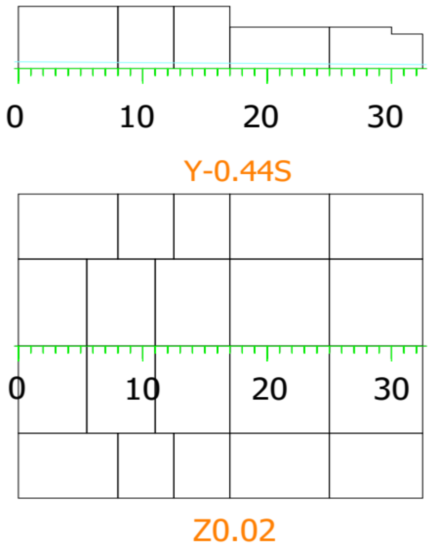
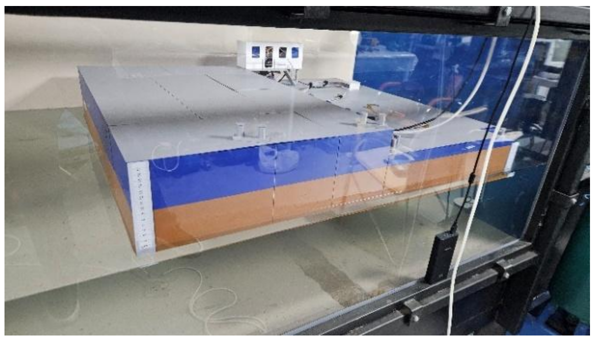


Figure 5: *Top and side view of the 1:25 scale Ro-Ro pontoon model (lightship condition)*

In parallel, the model was analyzed with the NAPA software, which generated hydrostatic data, righting lever GZ curves, and intact stability criteria. The resulting GZ curve of the model showed a maximum righting lever



at moderate heel angles, similar to the behavior observed in the full-scale pontoon. Together, these experimental and numerical results established a solid basis for comparative analysis with the real structure.

Figure 6: *Scale model of the pontoon during the inclining test*

The stability assessment of the 1:25 scale model, illustrated in Figure 7, highlights the behavior typical of reduced-scale structures. The righting lever (HPHI) rises sharply at small heel angles, reaches a maximum around 20°, and then decreases gradually while remaining positive up to nearly 90°. This evolution shows that although the model has very small displacement and dimensions, its stability curve preserves the overall trends observed in the full-scale pontoon.

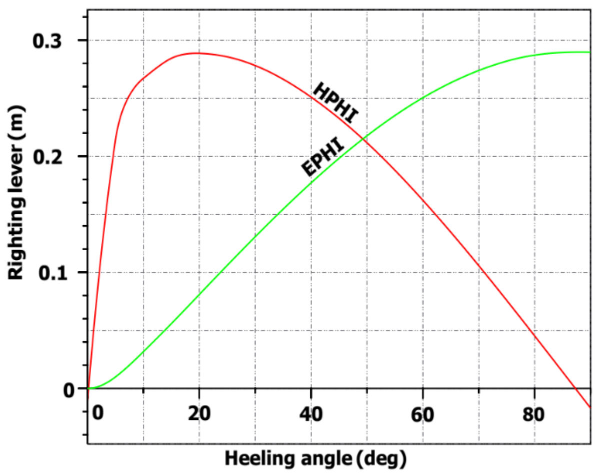


Figure 7: *Righting lever (GZ) curve of the 1:25 scale pontoon model in lightship condition*

The evaluation of the 1:25 scale model according to the International Code on Intact Stability shows that all intact stability criteria are satisfied. The results derived from the numerical analysis and the corresponding EPHI (area under the righting lever curve) confirm the consistency of the model's hydrostatic behavior:

- Up to 30°, the EPHI reaches 0.131 m·rad, exceeding the minimum requirement of 0.055 m·rad;
- At 40° of heel, the cumulative area attains 0.177 m·rad, exceeding the 0.09 m·rad criterion by a substantial margin;
- Between 30° and 40°, the incremental area is approximately 0.046 m·rad, higher than the 0.03 m·rad criterion;
- The maximum righting lever (HPHI) is approximately 0.29 m at 20° of heel;
- The GZ value at 30°, also about 0.28 m, confirms compliance with the minimum required 0.20 m.

The maximum lever occurs slightly earlier than the typical recommendation (≈20° instead of ≥25°), which is a predictable behavior for pontoon-type geometries characterized by a wide beam and low draft. Despite the smaller scale, the 3D-printed model exhibits a righting lever curve that follows the same trend as the full-scale pontoon, demonstrating that the model accurately reproduces the hydrostatic stability characteristics of the real structure.

5. Comparative Analysis of the Two Stability Assessments

The comparison between the full-scale pontoon and the 1:25 scale model shows a clear similarity in the shape of their stability curves GZ. In both cases, the righting lever reaches its maximum at moderate heel angles, around 20°, and gradually decreases with further inclination. This trend confirms that the scale model reproduces the overall stability characteristics observed in the full-scale pontoon.

Differences are observed in the absolute values: for the real pontoon, the maximum righting lever is in the order of meters, while for the scale model it remains below one meter. These differences are explained by scaling effects and the significantly lower mass of the 3D-printed prototype. Nevertheless, when the results are interpreted in proportional terms, relating the model's response to that of the full-scale structure, a consistent correlation can be observed.

The comparative values of the righting lever (HPHI) and the areas under the GZ curves (EPHI), for heel angles between 0° and 90°, are presented in Table 2. The analysis confirms that although absolute values differ, the scale model accurately reproduces the curve shape and the position of the maximum stability point, supporting its relevance for hydrostatic stability validation studies.

Table 2: *Comparative values of the GZ curve for full-scale and scale model pontoons*

HEEL (deg)	HPHI Model (m)	HPHI Real (m)	EPHI Model (mrad)	EPHI Real (mrad)
0	-0.01	-0.01	0	0
5	0.21	5.35	0.01	0.301
10	0.27	6.75	0.032	0.84
15	0.28	7.21	0.056	1.452
20	0.29	7.33	0.081	2.088
30	0.28	7.09	0.131	3.355
40	0.25	6.42	0.177	4.54
50	0.21	5.4	0.218	5.576
60	0.16	4.14	0.25	6.412
70	0.11	2.72	0.274	7.013
80	0.05	1.2	0.287	7.356
90	-0.02	-0.38	0.29	7.428

6. Conclusions

This study demonstrated the relevance of combining numerical and experimental methods for the evaluation of hydrostatic stability of Ro-Ro pontoons. The full-scale pontoon, analyzed with the NAPA software and validated by inclining tests, provided a reliable reference framework for comparison with the 1:25 scale model.

The physical model, manufactured by 3D printing using Fused Deposition Modeling (FDM), reproduced the general features of the stability curves and the position of the maximum stability point, confirming its applicability as a validation method. Although absolute values differ significantly, these variations are justified by scaling effects, and the proportional correlation between the model and the real structure shows satisfactory consistency.

Therefore, the combination of numerical modeling and physical testing provides a complementary and reliable approach for verifying the hydrostatic stability of floating structures, reinforcing the usefulness of scale models in applied mechanics research.

7. References

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