



ITTC2024

30TH INTERNATIONAL TOWING TANK CONFERENCE
22–27 SEPTEMBER 2024 | HOBART TASMANIA AUSTRALIA

STABILITY IN WAVES

SiW

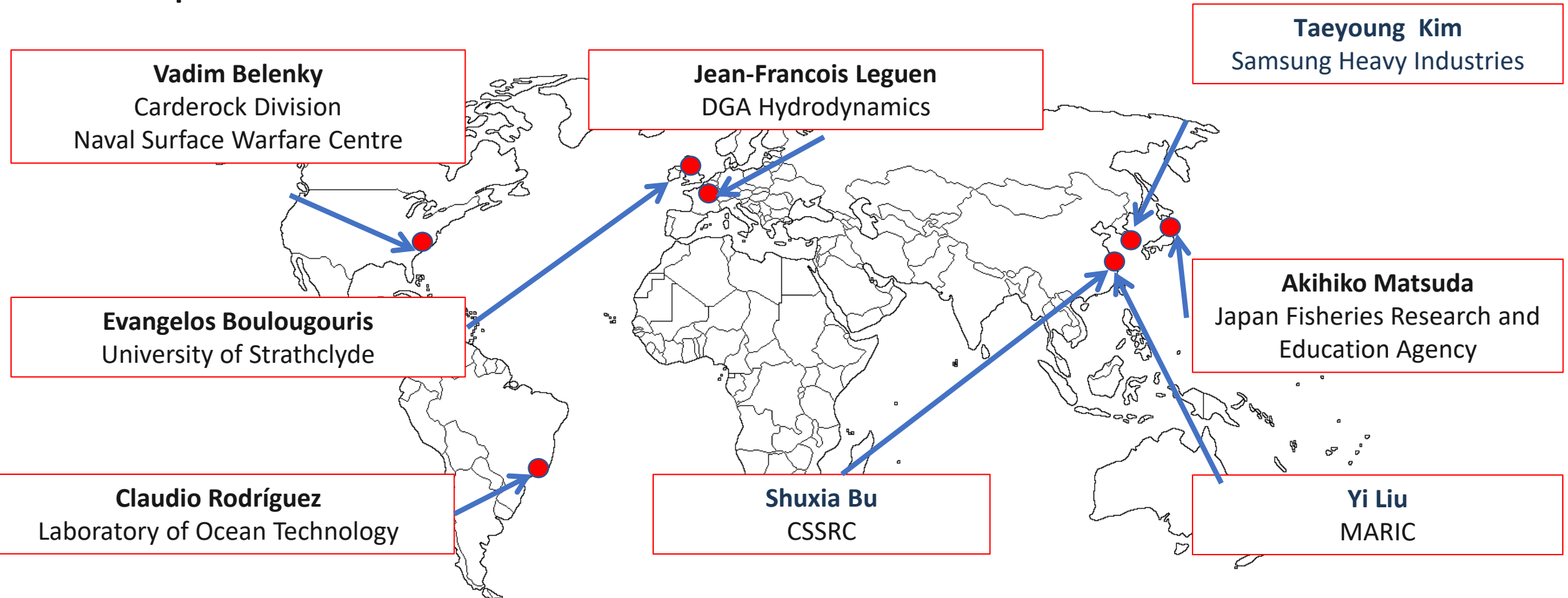
Membership:

Chairman : **Vadim Belenky** (Carderock Division, Naval Surface Warfare Centre, USA).
Secretary : **Jean-François Leguen** (DGA Hydrodynamics, France).
Members : **Evangelos Boulougouris** (University of Strathclyde, UK),
Shuxia Bu (China Ship Scientific Research Centre, China),
Taeyoung Kim (Samsung Heavy Industries, South Korea),
Yi Liu (MARIC, China),
Akihiko Matsuda (National Research Institute of Fisheries Engineering, Japan),
Claudio Rodríguez (Laboratory of Ocean technology, Brazil).

Stability in Waves

ITTC2024

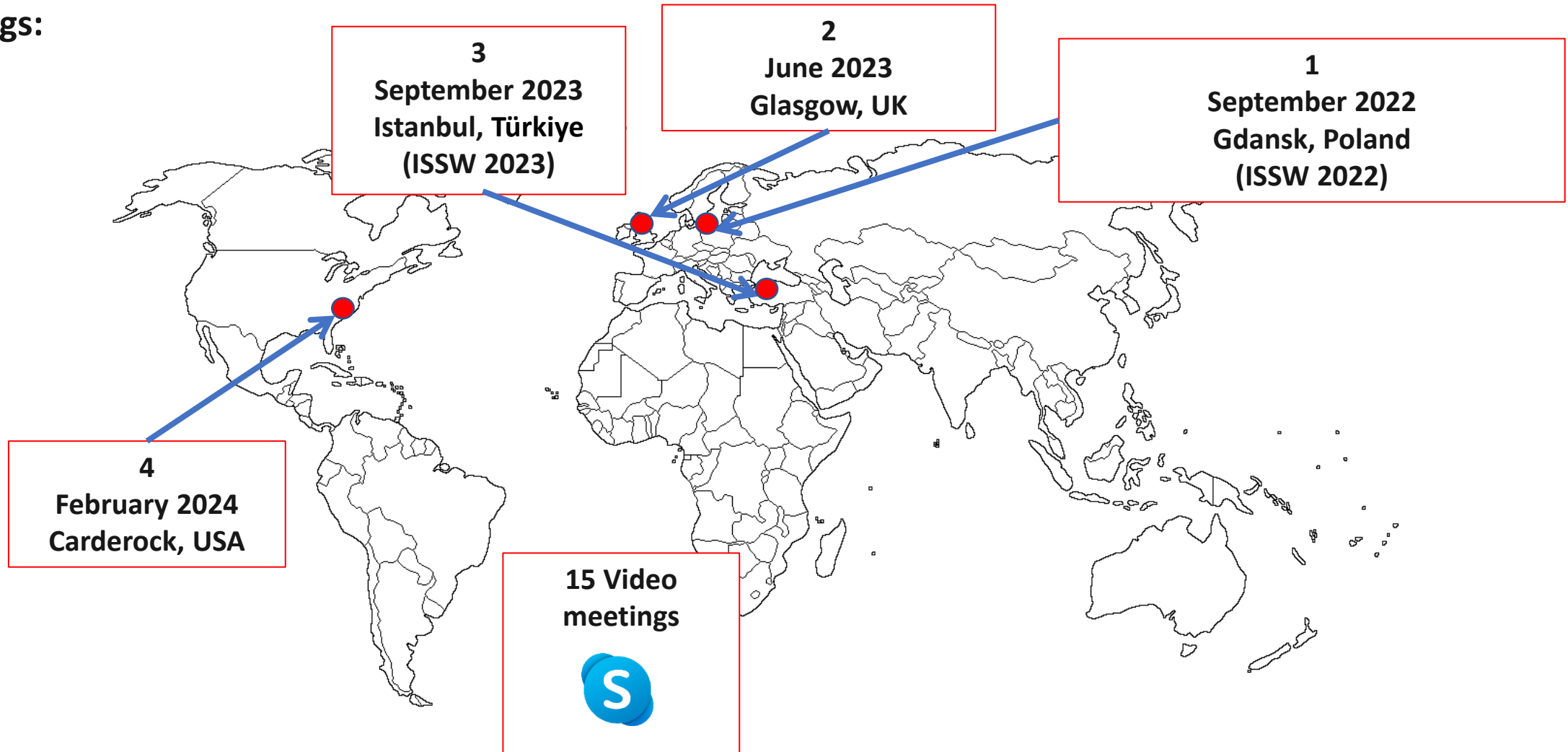
Membership:



Stability in Waves (2021-2024)



Meetings:



Stability in Waves

ITTC2024



GDANSK

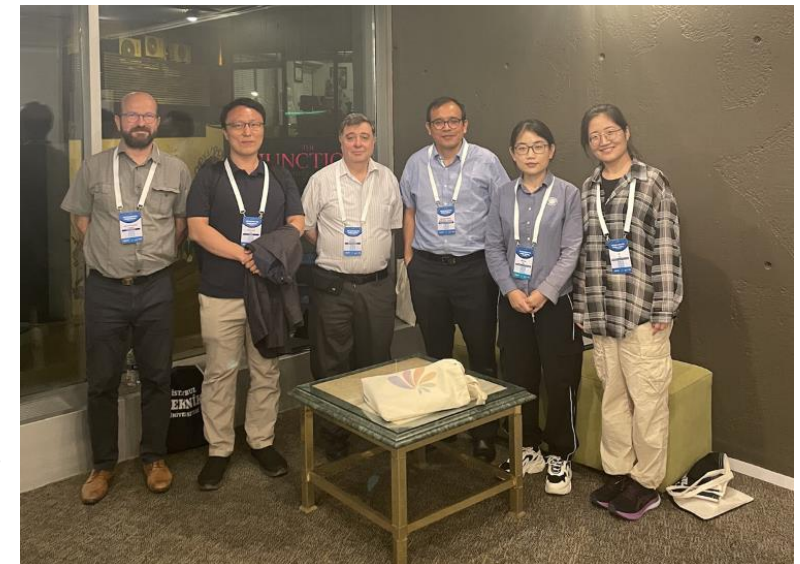


GLASGOW

CARDEROCK



ISTANBUL



Term Of Reference

1. Update the state-of-the-art for predicting the behavior of bottom founded or stationary floating structures, including moored and dynamically positioned ships, emphasizing developments since the 2021 ITTC Conference. The committee report should include sections on:
2. Review ITTC Recommended Procedures relevant to stability, including CFD procedures, and
3. Update ITTC Procedure 7.5-02-01-08, Single Significant Amplitude and Confidence Intervals for Stochastic Processes when new information becomes available.
4. Develop new ITTC recommended procedures in support of direct stability assessment within 2nd generation IMO intact stability criteria:
5. Develop a new procedure, Computational procedure for instantaneous GZ curve during time-domain numerical simulation in irregular waves.
6. Investigate the current state of the art on flooding dynamics of damaged ship in waves, including EFD and CFD.
7. Continue the identification of benchmark data for validation of stability-in-waves predictions.

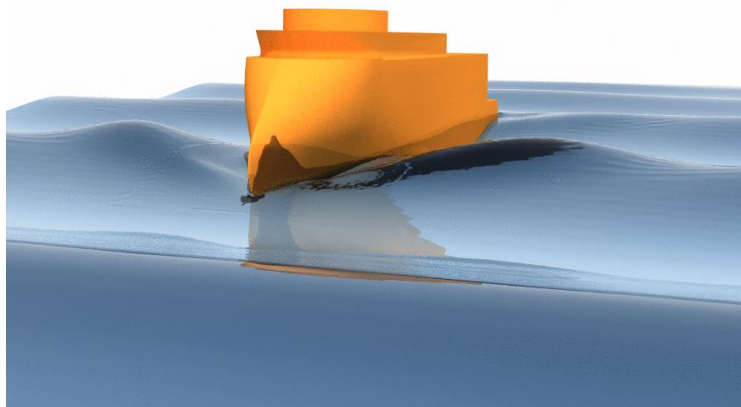


Domain Knowledge and Enabling technology

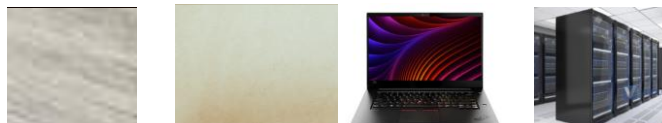
Theoretical Solution

$$\ddot{\varphi} + n_{\varphi}^2 \varphi + 2\mu\dot{\varphi} + \mu_3 \dot{\varphi}^3 + \alpha_3 \varphi^3 = 0.$$
$$\varphi(t, \varepsilon) = a \cos \theta + \varepsilon \left(\frac{1}{32 n_{\varphi}^2} \alpha_3 a^3 \cos 3\theta + \right.$$
$$\left. \frac{1}{32} \mu_3 n_{\varphi} a^3 \sin 3\theta \right) + \varepsilon^2 \left(\frac{1}{64} \mu \mu_3 a^3 \cos 3\theta - \right.$$
$$\left. \frac{21}{1024 n_{\varphi}^4} \alpha_3^2 a^5 \cos 3\theta + \frac{1}{1024 n_{\varphi}^4} \alpha_3^2 a^5 \cos 5\theta + \right.$$
$$\left. \frac{3}{64 n_{\varphi}^3} \mu \alpha_3 a^3 \sin 3\theta + \frac{3}{256 n_{\varphi}^3} \alpha_3 \mu_3 a^5 \sin 3\theta + \right.$$
$$\left. \frac{1}{256 n_{\varphi}^3} \alpha_3 \mu_3 a^5 \sin 5\theta + \frac{15}{1024} \mu_3^2 n_{\varphi}^2 a^5 \cos 3\theta - \right.$$
$$\left. \frac{3}{1024} \mu_3^2 n_{\varphi}^2 a^5 \cos 5\theta \right).$$

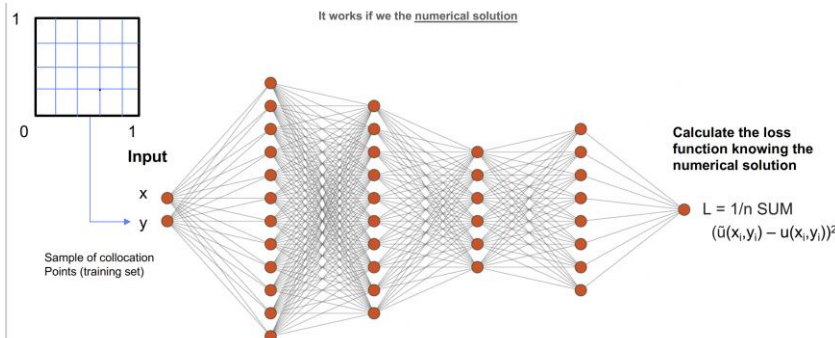
Numerical Method



Experimental Technique

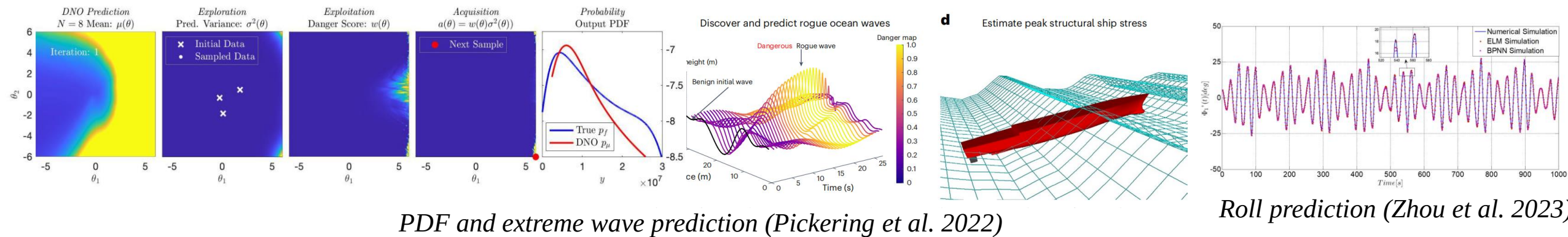


Machine Learning Model



Data-driven / Physics-informed
Fast and Efficient
model : ANN, Regression Tree, Deep
Learning,
Reinforcement learning,....

- Pickering et al. (2022)** addressed a computational framework by combining output-weighted training schemes in Bayesian experimental design (BED) with an ensemble of deep neural operators (DNOs). It is scalable artificial intelligence (AI)-assisted experimental infrastructure that can efficiently discover and forecast extreme events.



Intact condition

Data-driven models based on neural networks have gained prominence in ship motion prediction, due to their ability to automatically discern the underlying patterns and relationships from extensive data without the need for prior knowledge and comprehensive mathematical analysis :

- Zhou et al. (2023)** propose a "grey box" algorithm consisting of a deep learning network and parametric roll equation to provide the parametric roll simulations;
- González et al. (2023a)** investigated the deployment of a ANN model for real-time forecasting parametric roll.

TOR 1A: POTENTIAL IMPACT OF NEW TECHNOLOGICAL DEVELOPMENTS ON THE ITTC

Damaged condition

- Challenges with Traditional Methods:

Rigidity: Not easily adaptable to evolving damage situations.

Computational Complexity: First principle-based methods require significant time and computational effort.

Limited Reliability: Simplified calculation approaches have lower reliability.

- Machine learning :

Real-time results with higher reliability.

Reduces computational burden compared to traditional methods.

Emerging technologies & Innovations

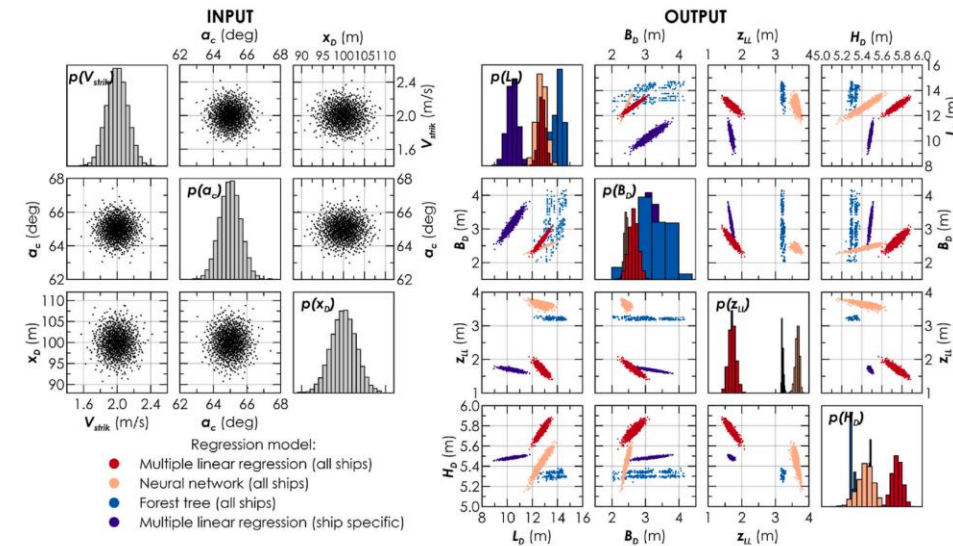
- Louvros et al. (2023) :**

Integrates Machine Learning (ML) and Case-Based Reasoning (CBR);

Uses pre-built databases for real-time damage analysis.

Relies on simple inputs like crew observations.

Effectively manages prediction uncertainties, especially for survival predictions.



Breach dimensions prediction (Mauro et al. 2023a)

- Mauro et al. (2023a)

Focus on real-time damage generation, developed a **surrogate mode** to estimate the location and dimensions of a potential breach for ship collisions for the first time.

Super-Element methods in SHARP software for scenario generation.

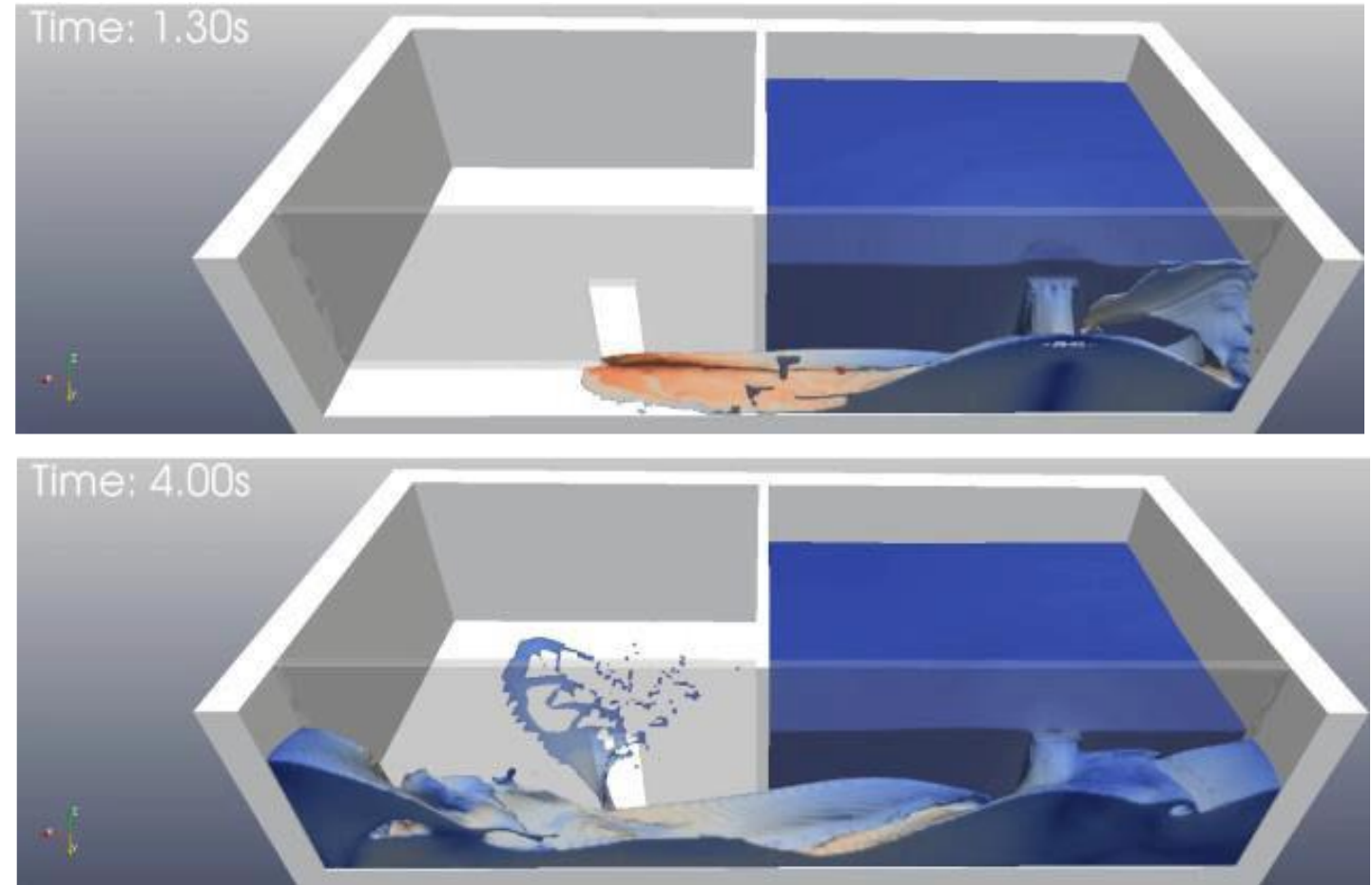
Multiple linear regressions. Neural networks.

Decision trees.

Emerging technologies & Innovations

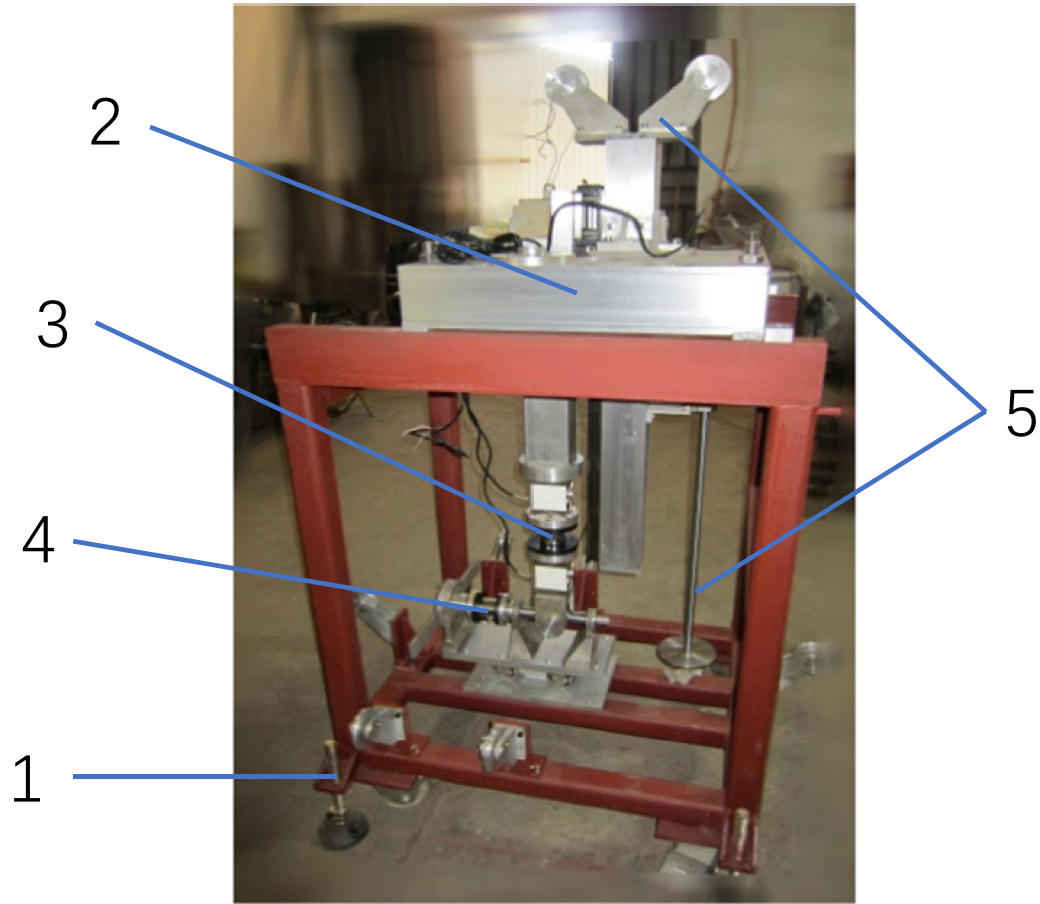
van't Veer et al. (2021):
Proposed a new flooding model with two modes of operation for internal flooding.

Lee et al. (2023, 2023a):
Analyzed the inertia of floodwater and the impact of trapped air in flooded compartments.



ComFLOW flooding snap-shots from **van't Veer et al. (2021):**

Experimental setup



Equipment for GZ curve in waves (Lu et al., 2017)

- Model testing is an effective means for investigating the GZ curve in the wave. CSSRC (Gu et al., 2014) constructed a partially restrained model test equipment for the GZ curve in waves
- Surge, sway and yaw motions are restrained, heave and pitch motions are free. Roll motion can be free or restrained depending on the test setup. Roll, pitch, and heave can be measured simultaneously. When roll is fixed at a given angle, the roll moment and the sway force are measured simultaneously, and the restoring moment can be recovered.

Experimental setup



Ship model of C11 Containership in partially restrained experiment (Bu et al. 2019)



Ship model of ONR tumblehome hull in partially restrained experiment (Bu et al. 2021)

This equipment has been used in model experiments with C11-class container ships and ONRTH with good results.

FLARE project (814753), Funded by EU Horizon 2020

<https://flare-project.eu/>

No comprehensive benchmark study for simulation tools since 2007, despite advancements.

Test cases:

- Flooding fundamentals

- Transient & progressive flooding

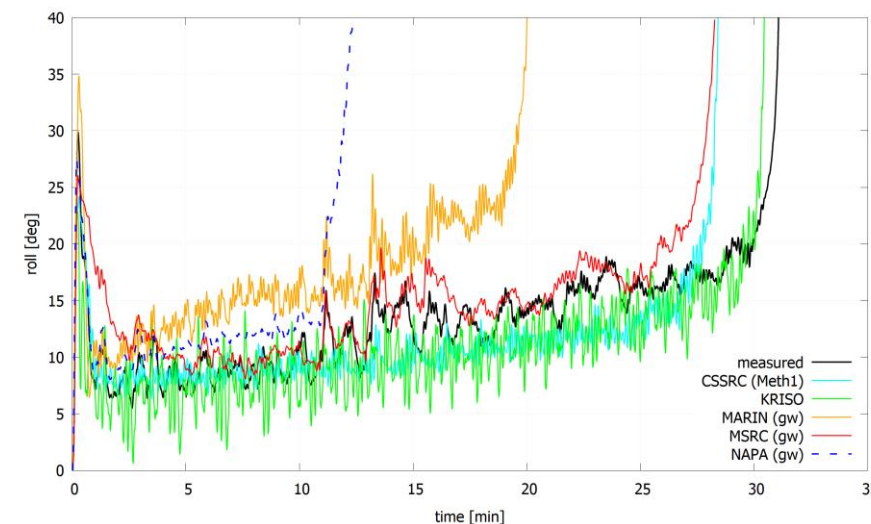
- Cruise & Ropax

Combination of experimental, CFD, numerical codes testing all aspects of flooding simulation (motions, floodwater accumulation, progressive flooding, effect of openings etc.)

Most codes performed well in basic flooding mechanisms but showed variation in roll angle predictions and time-to-capsize.

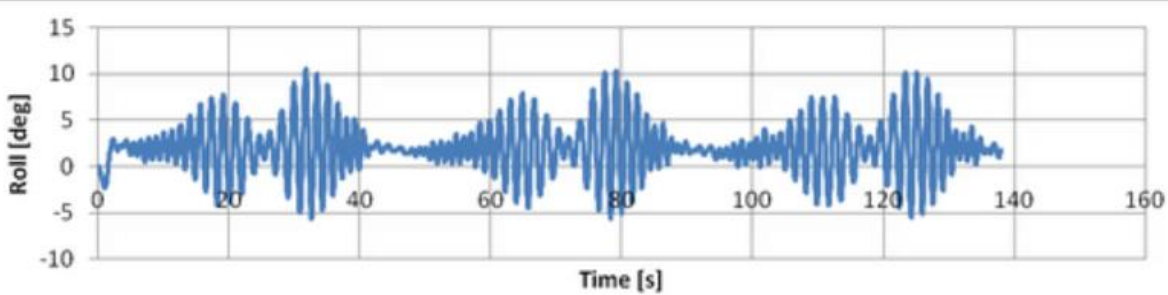


Floating model with the breach opening closed
(courtesy of MARIN)

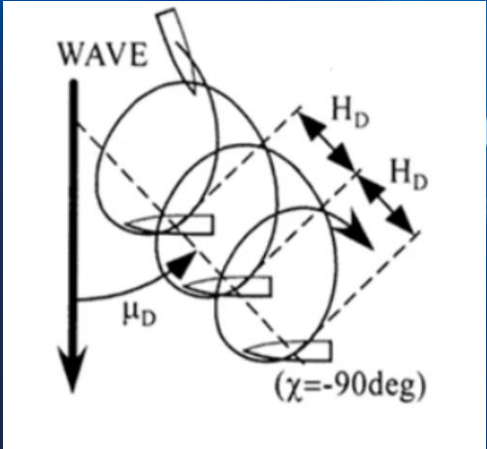


Roll angle in transient flooding and capsizing in waves

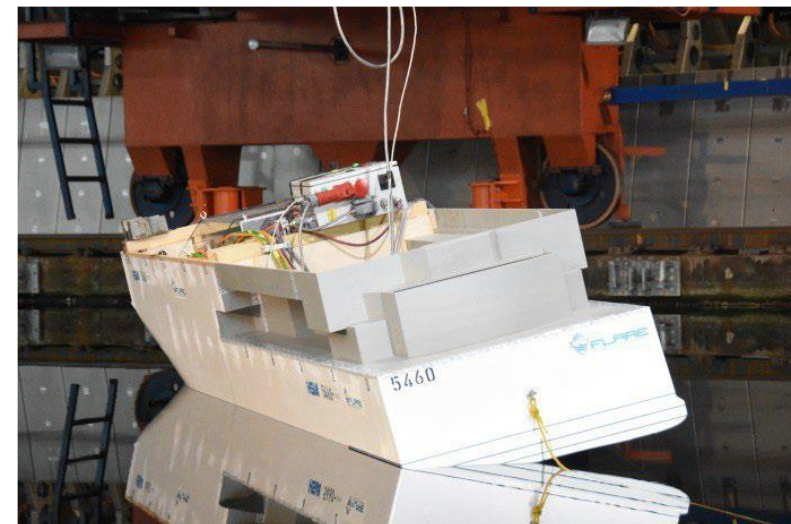
SIMMAM 2020 (www.simmam2020.kr)



1	2	3	4	5
KVLC2-deep	KVLC2-shallow	KCS deep	KCS shallow	ONRT
1.1 Test data by HMRI	2.1 Test data by BSHC	3.1 Test data by JMU	4.1 Test data by KRISO	5.1 Test data by SNU
1.1.1: Static drift 1.1.2: Drift & yaw	2.1.1: Static drift 2.1.2: Drift & yaw	3.1.1: Static drift 3.1.2: Drift & yaw	4.1.1: Static drift 4.1.2: Drift & yaw	5.1.1: Static drift 5.1.2: Drift & yaw
1.2 Test data by MARIN	2.2 Test data by MARIN	3.2 Test data by MARIN	4.2 Test data by MARIN	5.2 Test data by IIHR
1.2.1: SP & 20°/20° ZZ PS 1.2.2: 35° TC PS	2.2.1: SP & 20°/5° ZZ PS 2.2.2: 35° TC PS	3.2.1: SP & 20°/20° ZZ PS 3.2.2: 10°/10° ZZ PS 3.2.3: 35° TC PS 3.2.4: 20°/20° ZZ SB	4.2.1: SP & 20°/5° ZZ PS 4.2.2: 35° TC PS	5.2.1: SP 5.2.2: 20°/20° ZZ PS 5.2.3: 35° TC PS
Waves	Trajectories of self-propelled ship	Turning circle 35 to PS Comparison of trajectories and derived characteristics	3.3 Test data by HU	5.3 Test data by IIHR
				5.3.1: 35° TC PS, starting in head waves



- **GZ Curve in Waves (CSSRC) :**
Change of the GZ curve under different wave conditions for a container ship with a fixed heel angle.
- **Kapsenberg et al. (2020)** - Benchmarking numerical simulation tools for parametric roll: Numerical simulations were compared to model tests in irregular waves, showing minimal difference despite large roll motions.
- **Valanto and Schumacher (2021):** Studied roll damping of intact and damaged ships under various conditions.
- **Pineau et al. (2022):** Developed a numerical tool for rapid assessment of damage in ship grounding accidents.
- **Bu et al. (2022, 2023, 2023a):** Conducted experiments on motion and internal water height of damaged ships, comparing results with intact states.
- **Shawn and Park (ISSW 2022)** On the Uncertainty Quantification of Roll Decay Test, ISSW 2022. Data of roll decay tests on ONR TH.



From **Valanto and Schumacher (2021)**

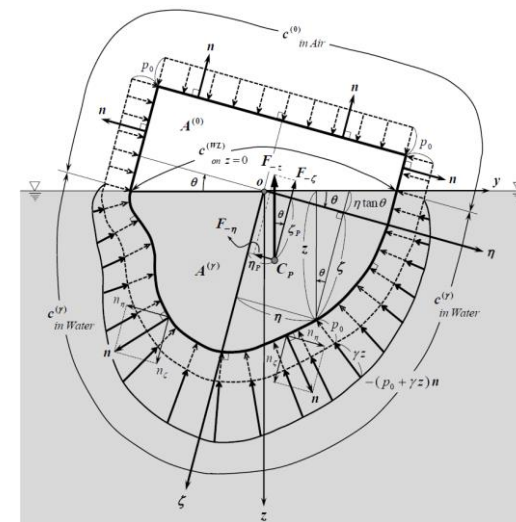
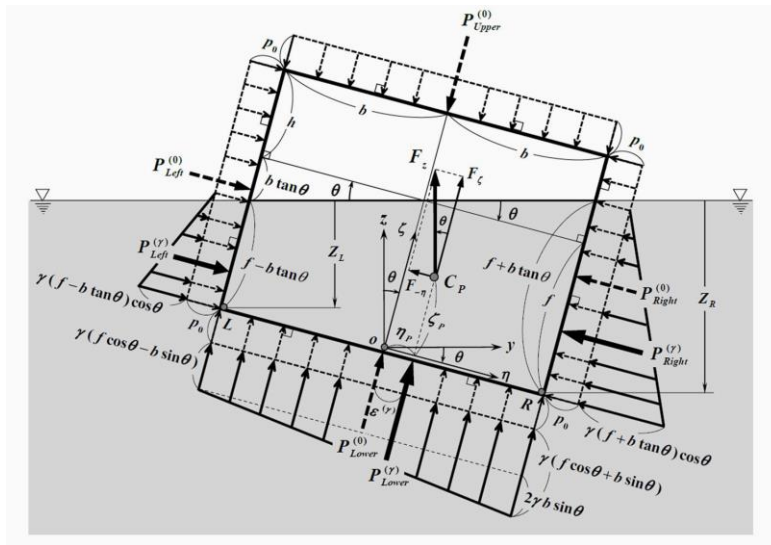
Fundamentals

- A not so trivial question : where is apply the Archimedes force?

Archimedes doesn't gave the answered for any type of floating bodies. Application of Ostrogradski theorem is not strictly sufficient.

It is known that this point is on the earth vertical throw the buoyancy centre.

- **Tsutomu Hori** (gave a demonstration that it is the center of pressure for any sections)



Deck immersion

- Munakata et al. (2021) examined the false-negative inconsistency issue in stability criteria for low-freeboard ships under dead ship conditions. Their model experiments showed that **deck immersion**, which **increases roll damping and reduces the effective wave slope coefficient**, is the main reasons.
- Subramaniam et al. (2021) investigated the **effect of trapped deck water on the roll dynamics of a low-weather-deck** offshore supply vessel (OSV) in both regular and irregular stern quartering waves.
- **Masamoto et al. (2023)** conducted experiments showing **how trapped water affects the stability of purse seiners in stern quartering seas**. They quantified this effect by analyzing the phase difference between the deck water motion and the ship's rolling motion.



Sloshing

Sloshing impact loads are typically not relevant to stability in waves but can **influence overall vessel dynamics**.

- **Wu et al.** (2021) improved the Moving Particle Simulation (MPS) method for two-dimensional sloshing problems and studied the **coupled swaying and rolling motions** at different loading rates, providing references for further studies on sloshing impacts on real ships.
- **Igbadumhe et al.** (2022) performed roll decay tests on an FPSO model with two-row prismatic tanks, finding that **increased liquid cargo, cargo location, and tank geometry affect vessel damping**.
- **Lyu et al.** (2022) considered the interaction between **sloshing and ship motions at forward speed**.
- **Lyu et al** (2022) developed an efficient hybrid (combined potential and viscous solver) numerical method to study ship-sloshing interactions at various forward speeds in oblique waves and found sloshing had the greatest influence on the ship's roll motions.

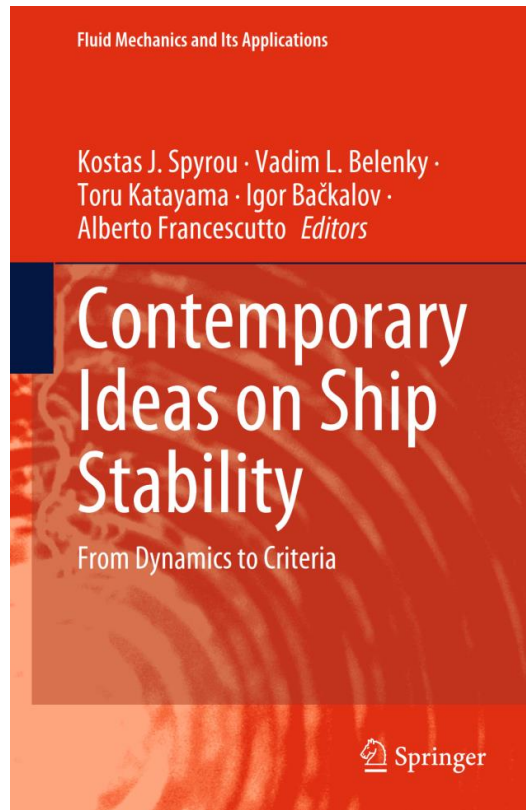
Motion in random waves

Evaluating rare events like maximum reactions over a ship's design life through direct numerical simulations is computationally intensive.

- For the “operational limitation” introduced by SGISC in MSC.1/Circ. 1627, **standard environmental conditions are replaced with specific ones**, affecting calculation parameters.
- Due to the nonlinearity of hydrostatic and Froude-Krylov forces, roll motion probability distributions can deviate from Gaussian distributions. **Maki** (2017) proposed treating the deviation as white noise and solving the Fokker-Planck-Kolmogorov (FPK) equation to find the distribution shape.
- **Maki et al.** (2022) use PLIM (PDF Line Integral Method) to predict the joint probability density function (PDF) of roll angle and rate.
- **Rajaraman and Hariharan** (2023) explore the steady-state ship rolling motion in random beam seas with nonlinear damping and restoring moments mathematically by using Hermite wavelets (HWM) .

Motion in random waves

- **Maki et al. (2021)** validated a method for predicting the joint PDF of roll angle and rate **using Monte Carlo simulations** for wave periods near natural roll periods.
- **Katayama et al. (2023)** researched suitable **non-Gaussian distributions** for short-term stability assessments.
- **Maruyama (2022b)** used a **stochastic averaging method** with a Hamiltonian to derive PDFs for roll amplitude and the Hamiltonian.
- **Zhou et al. (2023a)** used **the synthetic moment method and Hermite transformation** to predict extreme rolling angles from limited observations, validated with the C11 container ship model.
- **Rajaraman and Hariharan (2023)** explored steady-state rolling motion in random beam seas using **Hermite wavelets**.
- **Chai et al. (2022)** studied excessive roll motion for dead ship conditions and parametric rolling using the **Gumbel and ACER methods** to predict extreme values.
- **Glutzer et al. (2023)** updated confidence interval construction for ship motion estimates in irregular waves, accounting for self-dependence.
- **Li et al. (2023)** simulated extreme roll motion of ONRH using a CFD solver in irregular beam waves, emphasizing the importance of including sway motion in stability analyses.



4th book in the series;
Previous books were
published in 2019,
2011 and in 2000

- The book summarizes advancement with selected papers from international stability workshops from 2013 through 2019, totally 42 chapters
- Comprehensive overview by the editor-in-chief
- Structure:
 - Development of the 2nd generation intact stability criteria (6)
 - History of stability (1)
 - Probabilistic method (9)
 - Parametric roll and operational measures (5)
 - Surf-riding and broaching-to (4)
 - Roll damping (4)
 - Damage stability (5)
 - Model experiments (3)
 - Accident investigation (1)
 - Cargo liquefaction and offshore structures (2)
 - Special crafts (2)

Special Issue of Ocean Engineering “Extreme Stochastic Dynamics of Ships”



- Total 20 paper published in 2022-24
- Inspired by long-term research program “A Probabilistic Procedure for Evaluating the Dynamic Stability and Capsizing of Naval Vessels” run by the US Office of Naval Research.
- 17 papers relevant to the committee have been reviewed, including:
 - Uncertainty quantification and self-repeating effect (2)
 - Direct counting (2)
 - Probabilistic properties of extreme rolling (2)
 - Probability of capsizing (2)
 - Extrapolation and statistical validation (5)
 - Operational guidance (2)
 - Reduced-order model (2)

Second Generation Intact Stability Criteria



E

4 ALBERT EMBANKMENT
LONDON SE1 7SR
Telephone: +44 (0)20 7735 7611 Fax: +44 (0)20 7587 3210

MSC.1/Circ.1627
10 December 2020

INTERIM GUIDELINES ON THE SECOND GENERATION INTACT STABILITY CRITERIA



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LONDON SE1 7SR
Telephone: +44 (0)20 7735 7611 Fax: +44 (0)20 7587 3210

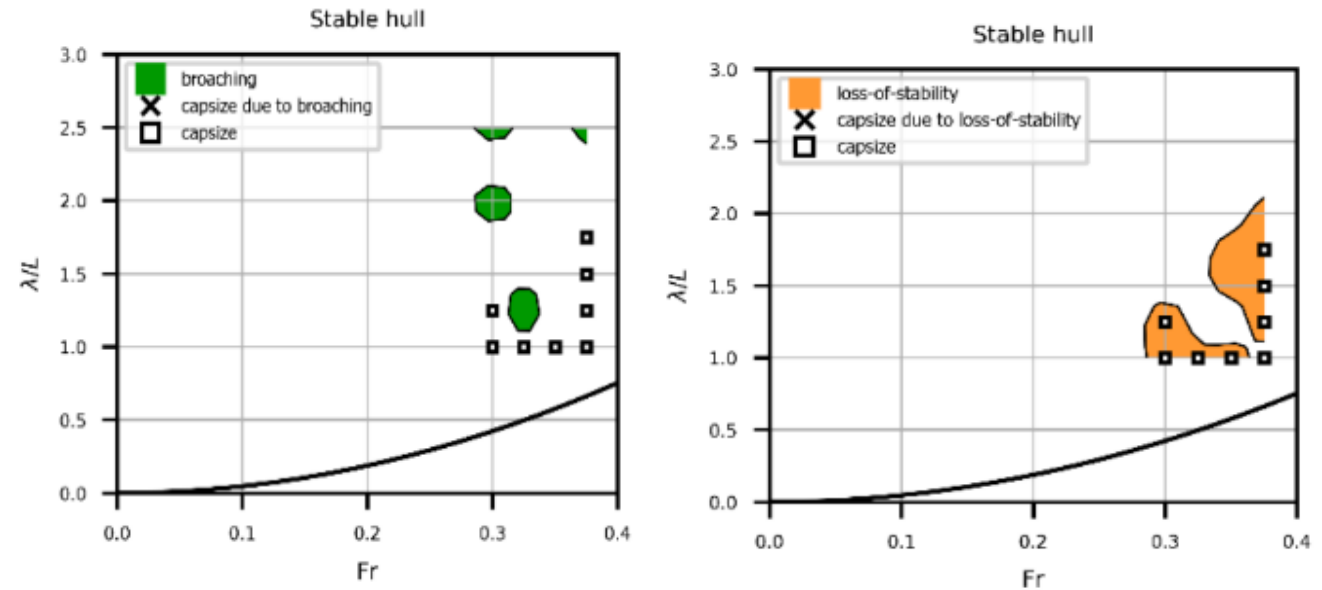
MSC.1/Circ.1652
26 April 2023

EXPLANATORY NOTES TO THE INTERIM GUIDELINES ON THE SECOND GENERATION INTACT STABILITY CRITERIA



Surf-riding / Broaching-to

Feng et al. (2023) examined the **level 2 surf-riding/broaching vulnerability criterion** and proposed improvements to the assessment procedures. The current procedure's limitation is not applicable to **waterjet propelled ships**, and second, the need for a practical method to estimate the wave surge force correction factor are addressed.

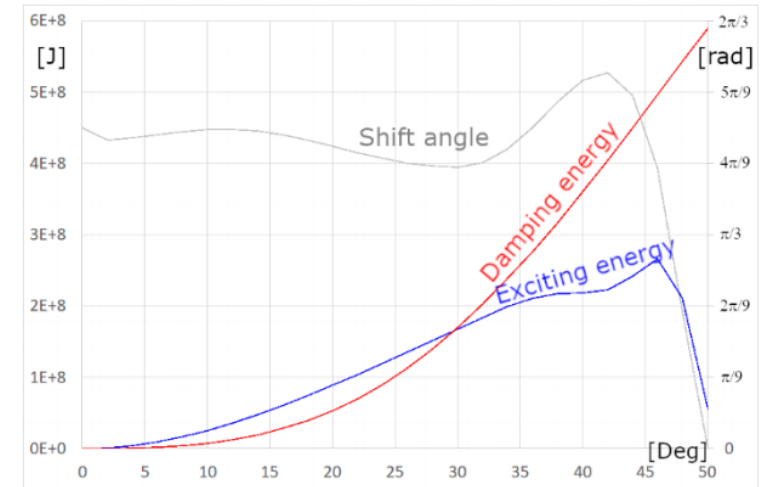


Broaching-to and pure loss of stability region. (Bonci, 2022)

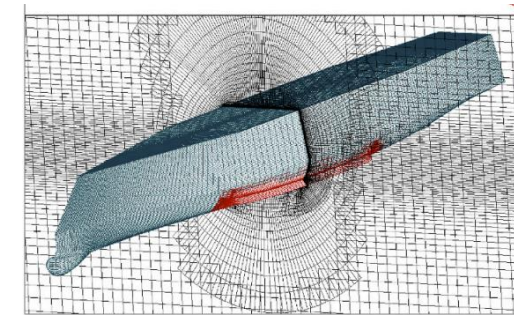
Bonci et al. (2022) explored the capsize dynamics of a frigate in stern quartering waves using nonlinear time-domain simulations. The effects of these maneuvering forces on ship capsize were examined.

Parametric roll

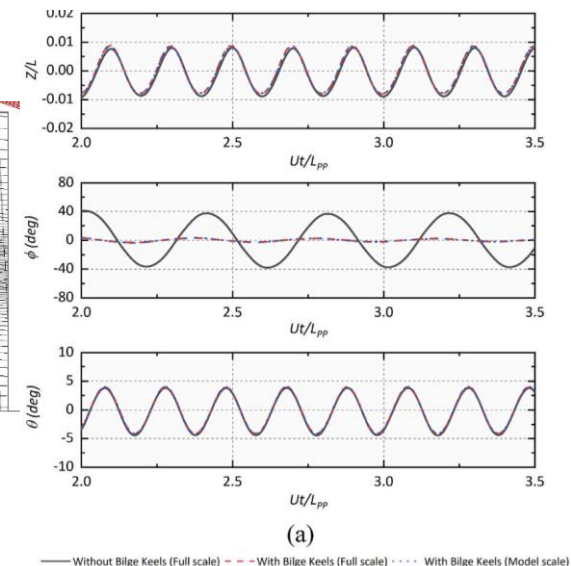
- **Luthy et al (2021, 2022)** extend the energy method to non-linear GZ for the prediction of parametric roll. Then the extended energy method is applied to several vessels chosen, providing an accurate estimation of the steady state roll amplitude at any speed within the range where parametric roll occurs.
- A number of examples of the operational restrictions imposed on the parametric rolling failure model are provided by **Hashimoto and Furusho (2021)**. They examined the effects of season, area, and route restrictions on the susceptibility to parametric rolling stability failure.
- **Liu et al. (2021)** presented a CFD prediction of a full-scale ship parametric roll in a regular head wave.



Damping and exciting energies and fitted. (Luthy et al,2021)

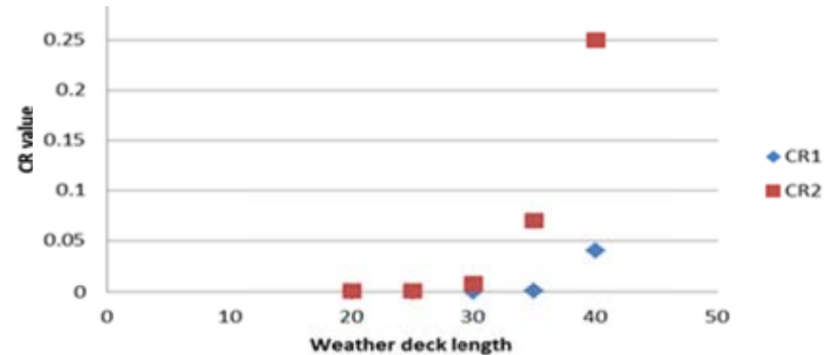


Liu et al., 2021

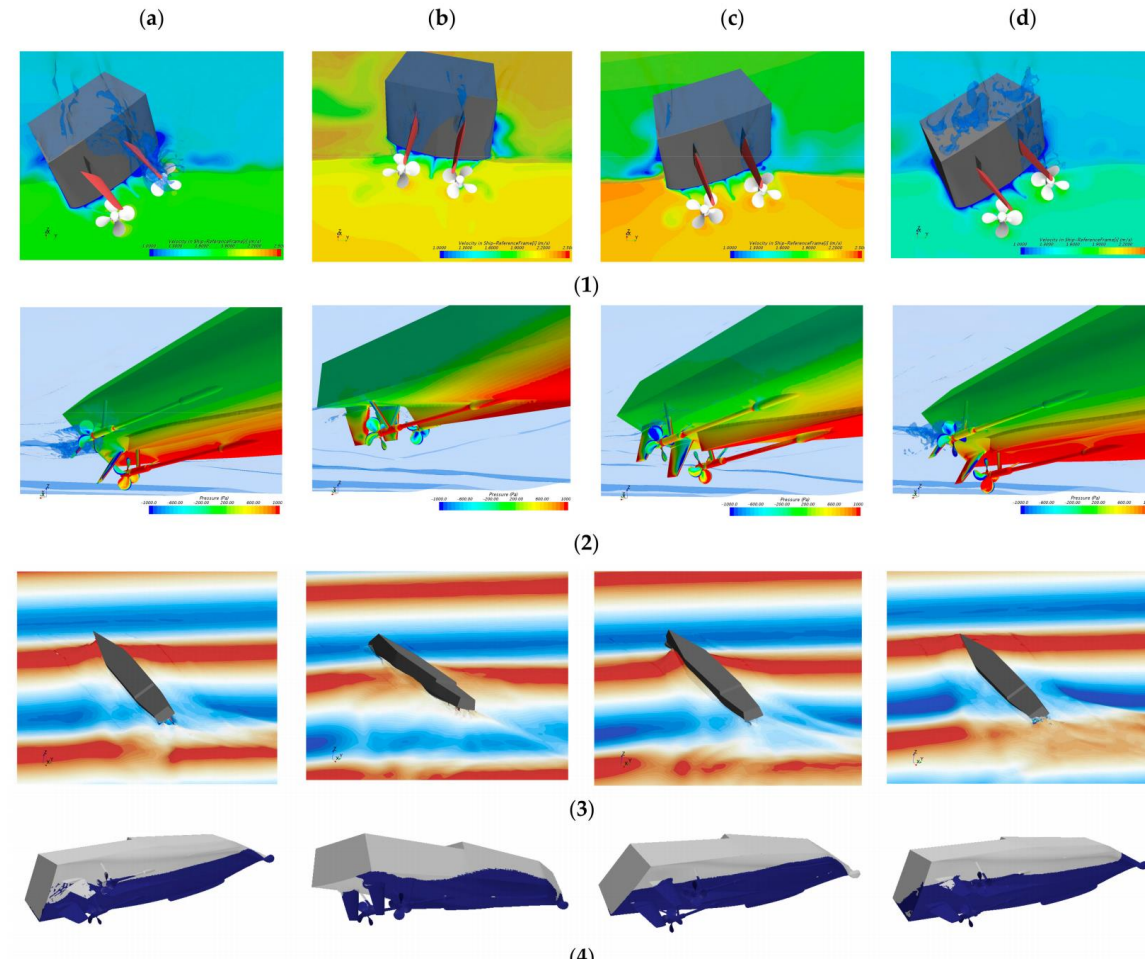


Pure loss of stability

- **Zeng et al. (2023)** carried out the CFD computation that simulates the pure loss of stability of a fully appended ONRTH in following waves.
- **Umeda et al. (2023)** considered inconsistency in vulnerability criteria for pure loss of stability encountered with offshore supply vessels, having an extended low deck.



Weather deck length vs CR value from Level 2 program. Umeda et al. 2023



Flow field variations, Zeng et al. 2023

Damage stability in waves

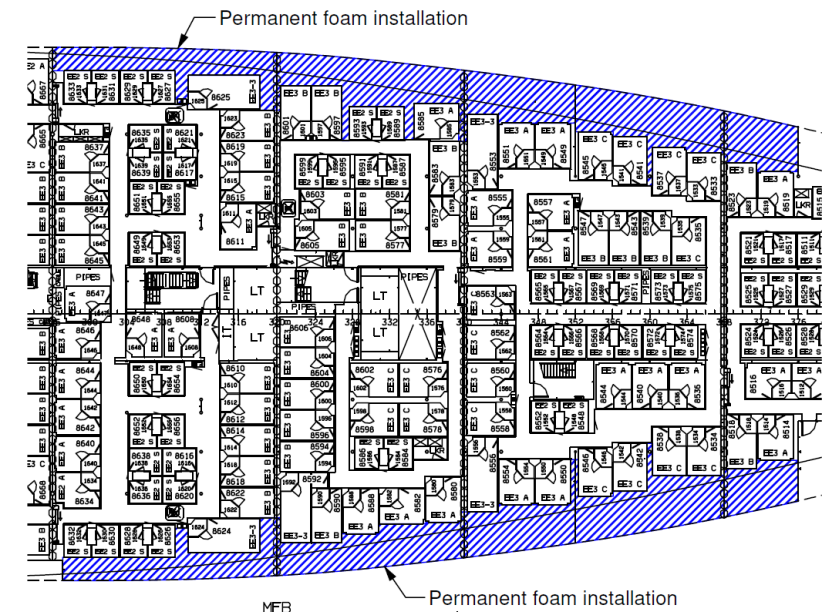
- **Vassalos et al. (2023a)** considered possible measures for improvement of survivability of Ro/Ro passenger ships after damage.
- **Atzamos et al. (2023)** focused on survivability-in-waves of cruise vessels after damage. A new formula was proposed for the s-factor.

Regulatory Frameworks

- **Vidić and Bačkalov (2022)**: Analyzed stability regulations for Large Inland Passenger Ships and the need for global harmonization.
- **Vassalos et al. (2022)**: Provided a statistical analysis of new damage breach distributions and their impact on damage stability.

Probabilistic and Statistical Methods

- **Duan et al. (2023)**: Proposed an improved probabilistic framework for survivability assessment of damaged ships in waves.
- **Vassalos et al. (2022a)**: Conducted sensitivity analysis on permeable volume and its effect on damage stability.

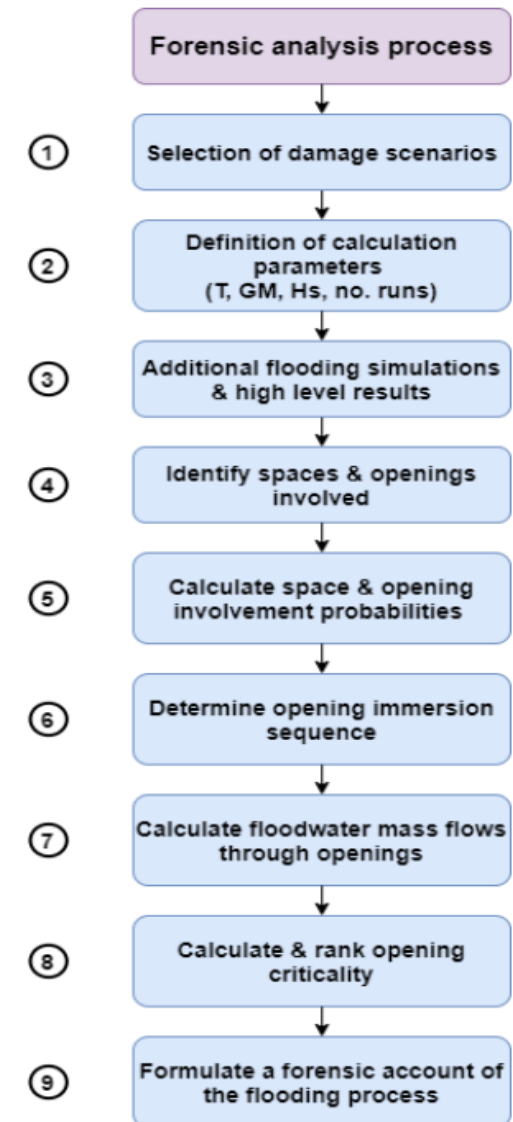


Foam installation (permeability change) in void spaces in the wing compartments of a cruise ship from **Vassalos et al. (2022a)**:

Damage stability in waves

Assessment methods

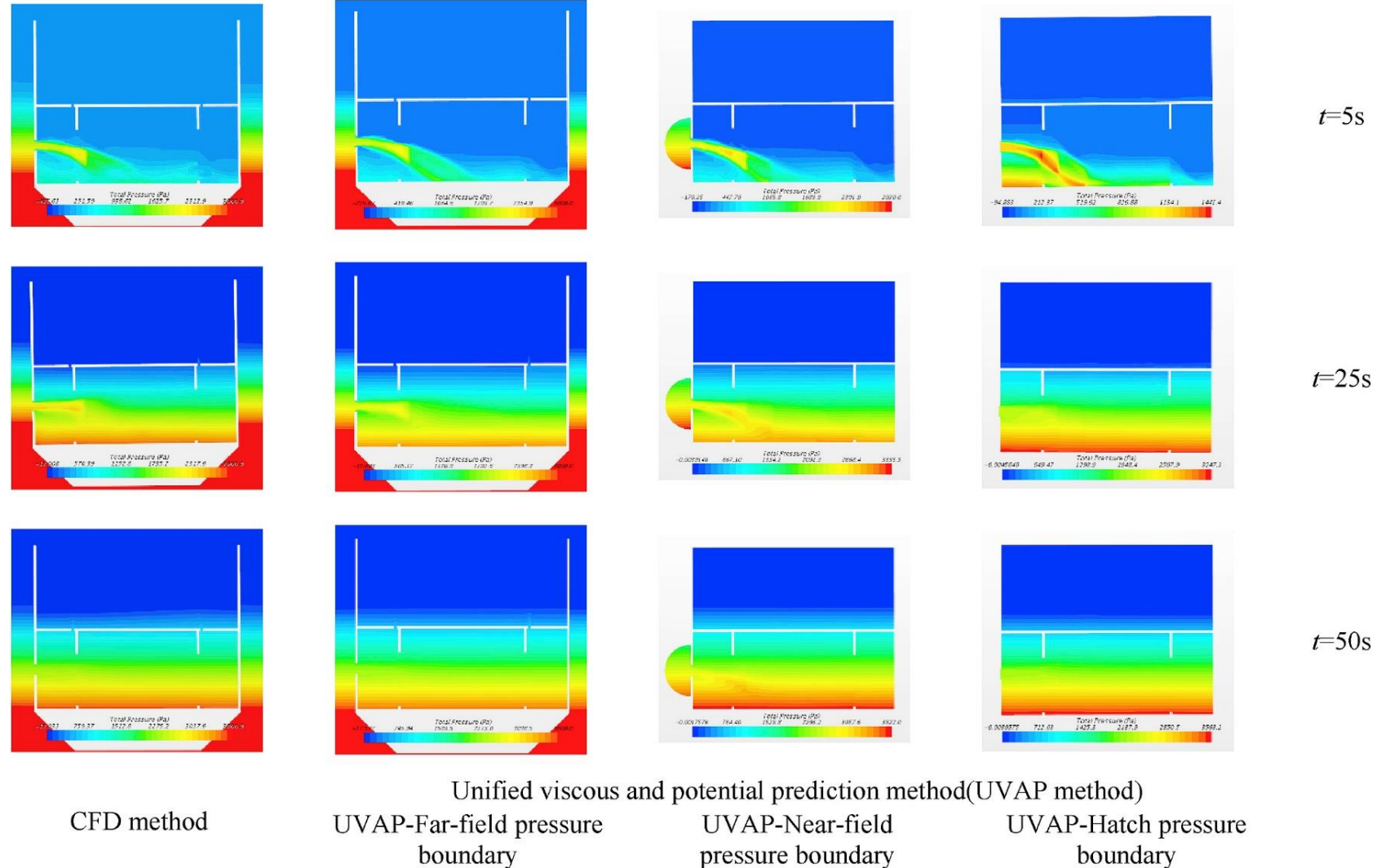
- **Mauro et al. (2021)**: Proposed three methods for damage assessment:
 - Static calculations
 - Energy absorbed during impact
 - Dynamic approach
- **Mauro et al. (2023)**: Introduced a hybrid two-level framework for stability assessment:
 - Level-1: Static damage stability
 - Level-2: Dynamic flooding simulation
- **Vassalos et al. (2021)**: Developed quantitative risk models and a new risk-based method for direct flooding risk assessment.
- **Bae et al. (2023)**: Proposed a quantitative risk assessment methodology with crash-worthy structural designs as Risk Control Options (RCOs).



Numerical tools

Bu et al. (2021): Combined a 3D time domain potential method with CFD to improve efficiency and accuracy in predicting damaged ship motion.

Bu et al. (2022, 2023, 2023a): Investigated motion and flooding of damaged passenger ships using experimental and numerical methods.

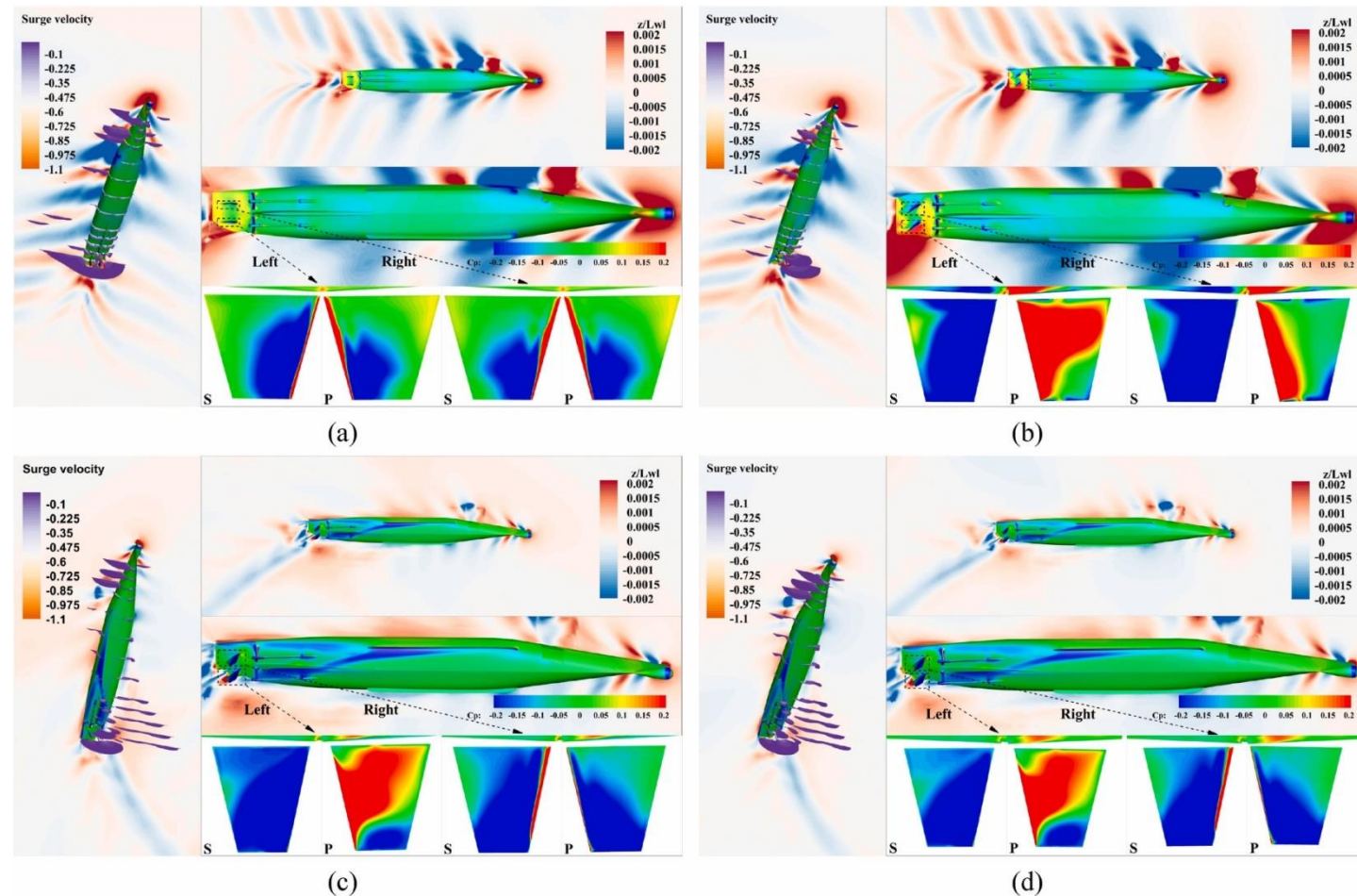


Numerical tools

Krüger et al. (2021): Extended Monte Carlo simulations for comprehensive damage stability calculations.

Dong et al. (2023): Simulated turning maneuvers of a combatant with a damaged bow compartment using an unsteady RANS solver and dynamic overset approach.

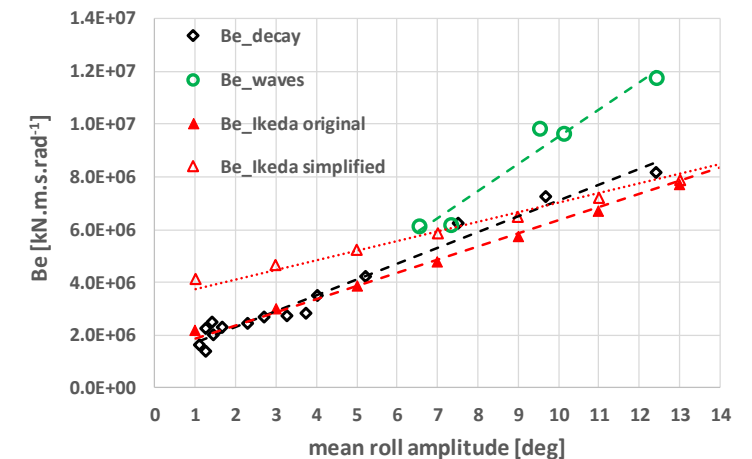
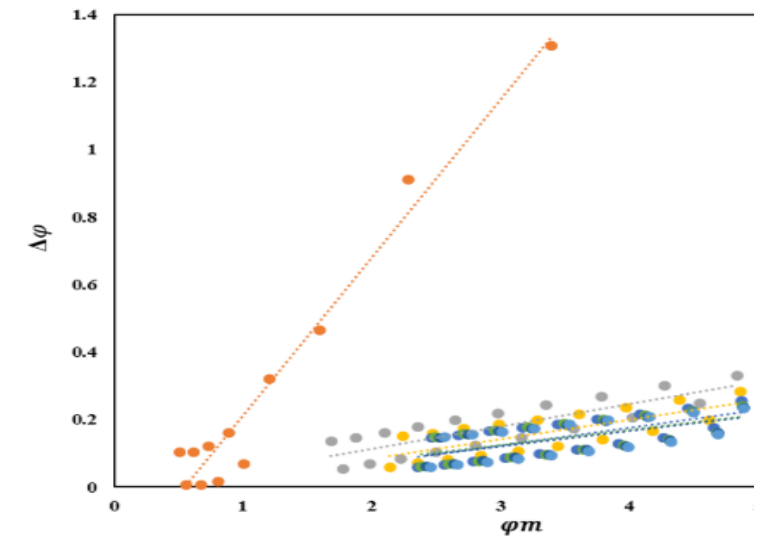
Kawamura and Hino (2023): Developed a method coupling MPS and Finite Volume Method (FVM) for simulating partially filled tanks.



Snapshots of the surface wave, surge velocity cross-sections as well as dynamic pressure distribution in different stages for the damaged ship from **Dong et al. (2023)**:

Roll damping

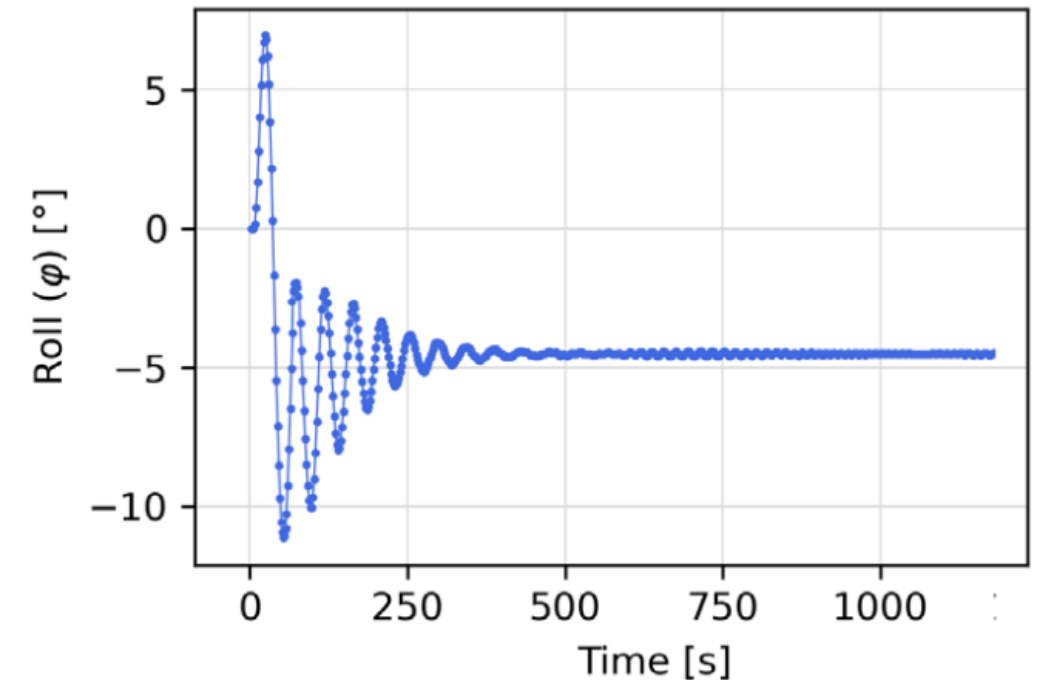
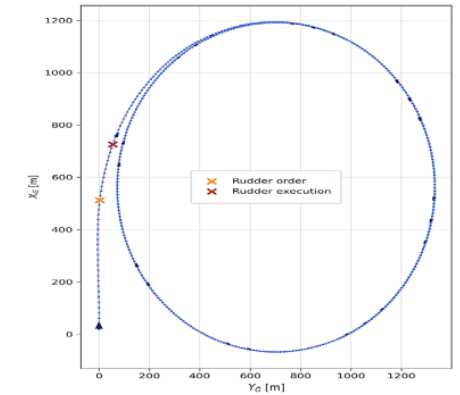
- Katayama et al. (2022a) corrected a typographical error of Ikeda's formula of the eddy-making component for naked hull.
- For predicting bigle-keel contribution into roll damping, CFD method are conducted. (Katayama and Yoshida ,2023; Wassermann and Abdel-Maksoud ,2023; Umeda et al.,2023)
- Chen et al. (2023) investigated the roll natural period and damping coefficients in finite depth condition by using CFD computations.
- Rodríguez et al. (2022) showed the high dependency on roll damping coefficients by investigating the numerical simulations of VLCC roll responses in waves. Roll damping coefficients were obtained from roll decay tests, calibration of experimental roll responses in waves, and Ikeda's method, respectively.



Linearized roll damping coefficients,
(Rodríguez et al. 2022)

High speed turn

- OMI doesn't regulate on this topic but some rules as naval rules does
- It could become needed, for example for autonomous ship (Hinz et al., 2022)

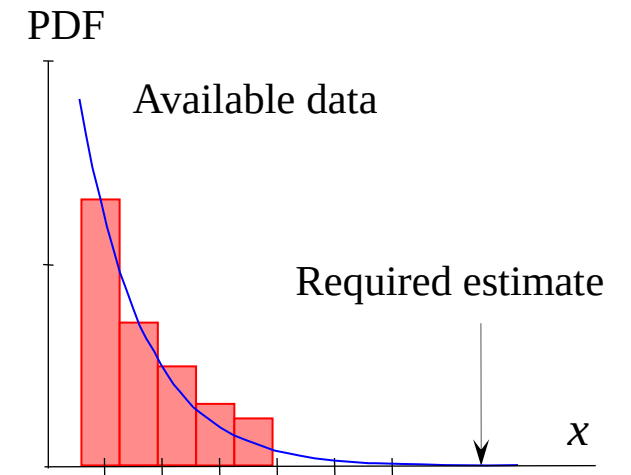


Extrapolation methods

An essential technique for probabilistic assessment of stability in waves.

Most of engineering-level numerical simulation tools for ship motion are too slow to observe stability failure directly.

- Extreme value theory
- Consideration critical wave groups (or single waves) and wave episodes
- Extrapolation over environmental conditions



Extreme value theory

- The extreme value theory states that the largest value in a sample of independent identically distributed variables tends to Generalized Extreme Value (GEV) distribution .
- A distribution above some large threshold can be approximated with Generalized Pareto Distribution (GPD) .
- Difficulties (**Anastopoulos and Spyrou, 2023**):
 - The shape parameter estimate is a subject for statistical uncertainty, leading to appearance of a right bound in a random location of tail. The GPD-based method fails to deliver a result if bound is below the extrapolation target .
 - Difficulty of comparison of the GPD outcome with Monte-Carlo and critical wave group results.
- Resolution : determine the type of the tail based on physical consideration
 - **Campbell et al. (2023)** modeled heavy tail with Pareto distribution with the Envelope Peak-over-Threshold (EPOT) method, which decreasing the uncertainty by several orders of magnitude.
 - **Belenky et al. (2024)** describes application of split-time method (MPM) for estimation of capsizing probability, using an exponential distribution for capsizing metric.
 - **Weems et al. (2023)** describe statistical validation of MPM of capsizing probability, and the split-time method with exponential tail was significantly better than that of GPD

Consideration critical wave groups (or single waves) and wave episodes

- Two basic ideas:
 1. The neighborhood of a large wave is almost deterministic (**Boccotti** 2000, 2014)
 2. Only certain critical wave groups can cause significant dynamic response
- **Anastopoulos and Spyrou** (2023a) provide an update on the development of the critical wave group method. The wave groups with period close to natural period are likely to be critical for the failure modes .
- Critical wave group is short. So the method offers sufficient computational efficiency to be used with model tests (**Anastopoulos et al.** 2016; **Bassler et al.** 2019) and CFD (Silva and Maki, 2021) .Initial condition handling method, suitable for CFD, where a deterministic wave group is embedded into previously simulated ship response is considered (Silva and Maki, 2021).
- **Mohammad and Sapsis** (2018) used a combination of an envelope of wave elevations and Gaussian-shape functions for detecting the wave groups. The problem of initial conditions is considered by Guth and Sapsis (2022) with a “stochastic prelude” approach to capture the transitional behavior.

Extrapolation over environmental conditions (currently over significant wave height only)

- The idea (**Tonguč and Söding 1986**):
 - Simulations are conducted in high sea states, where stability failure is observable.
 - Results are extrapolated to lower sea states, where direct observation is not feasible due to high computational costs.
- **Anastopoulos & Spyrou (2022, 2023b)** presented a formal argument on the equivalency between Extrapolation over wave heights and Critical wave group method. Proposed two improved formulae for extrapolation that maintain simplicity, which included in the revised ITTC procedure 7.5-02-07-04.6.
- **Shigunov (2023)** focused on reducing computational time through statistical extrapolation, found that failure rate extrapolation over significant wave height does not satisfy criteria with a sample size of 20, and satisfies criteria with a sample size of 200.

Direct Stability Assessment

Comparison/analysis of direct counting methods (mean upcrossing rate, time to first event, time between events, cycle amplitudes and maximum value over an interval) – ship roll motion data, **independence** of stability failure rate events;

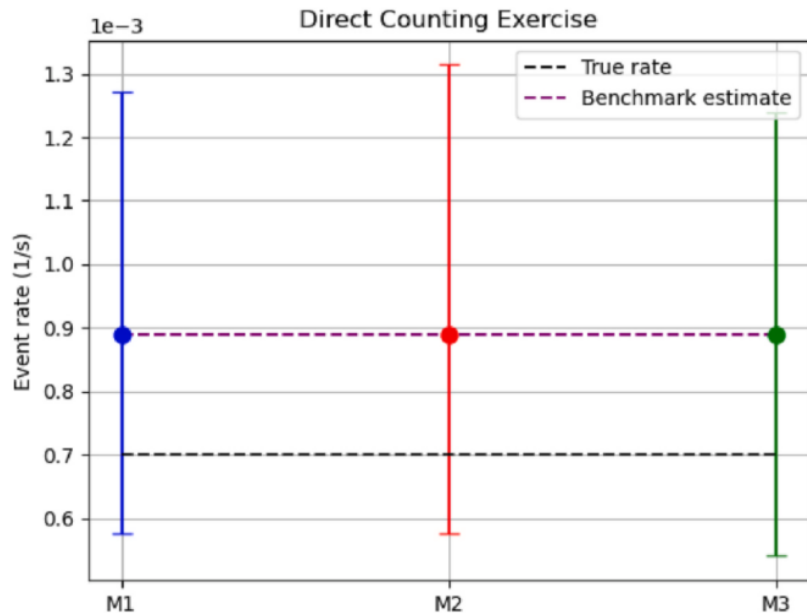


Fig. 8. Estimate of failure rate and upper and lower boundaries of its 95% confidence interval for $N = 25$ (using exposure time 1 s in M2 method, which led to $N^* = 25$). Wandji et al. (2024)

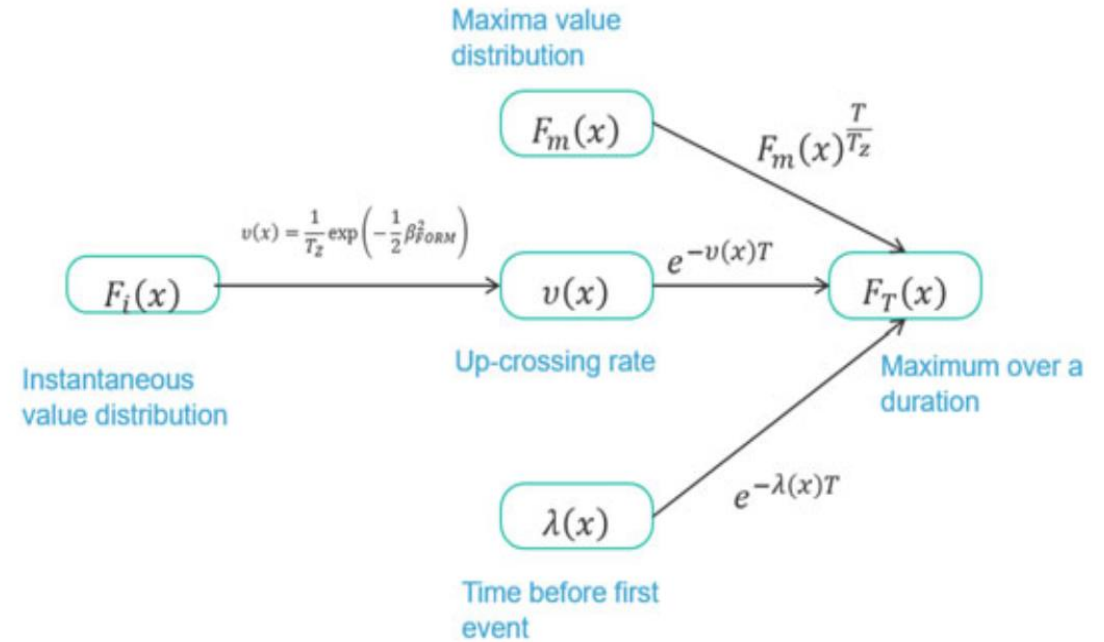


Fig. 23 Relation between different of statistical estimates Wandji (2023)

Shigunov et al. (2022), Wandji et al. (2023), Wandji et al. (2024): Comparison of IMO's direct counting procedures: **exponential distribution, statistical frequency and binomial distribution** – synthetic data, based on Poisson's model.

Direct Stability Assessment

- **Matsubara et al. (2023)**: validation study on **critical wave method for broaching under long- & short-crested irregular seas**. Conservative estimates of the probability of a large heel due to broaching, but much shorter computational time.
- **Weems et al. (2023a)**: enhanced the **multifidelity SimpleCode** by introducing ship and sea-way-dependent **diffraction and radiation coefficients** to the hydrodynamic forces from potential flow seekeeping simulations. Long-wave assumption (roll) and wave pressure decay negligence (pitch) are limitations

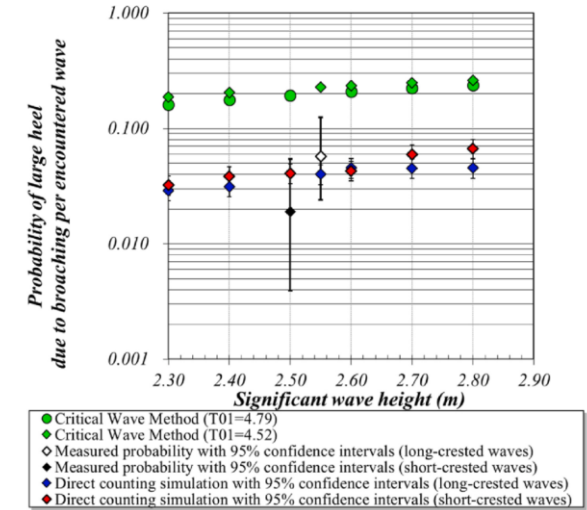
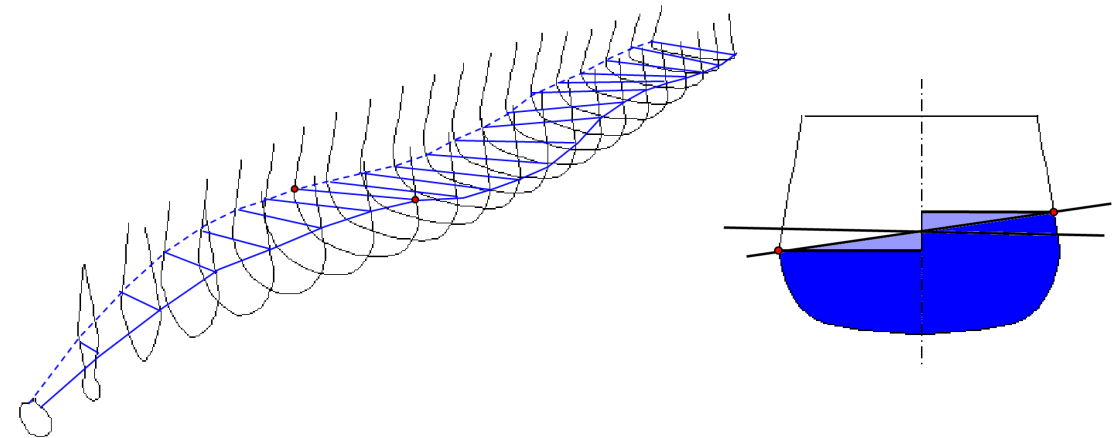


Fig. 6. Comparison of the probability of a large heel due to broaching among the experiment, the direct counting simulation, and the critical wave method.



Introduction to R&D in Ship Stability and Numerical Modelling

Overview:

- The advancement of ship stability modeling and simulation has seen significant progress, but there remains a need for research and development (R&D) to **improve** methods in both **experimental** and **numerical** modeling techniques.

Key Focus Areas:

- The focus is on understanding the complex dynamics of ship stability in **stochastic environments**, where randomness in the seaway makes predictions challenging.
- A significant emphasis is placed on **improving computational models**, especially in reducing the time and resources required for simulations without compromising accuracy, through methods like **reduced-order modeling** and **machine learning**.

Stochastic Approaches and Statistical Extrapolation

Stochastic Modeling:

- **Anastopoulos & Spyrou (2022, 2023):** Used [stochastic wave group](#) theory to analyze [capsize risks in mild seas](#). They highlighted issues with IMO's wave height formula, suggesting improvements using stochastic wave group theory.
- **Maruyama et al. (2022):** Modelled the [non-Gaussian excitation](#) process by using the linear filter and non-memory transformation.

Numerical Methods and Extrapolation:

- **Silva & Maki (2022):** [Combined CFD, neural networks, and critical wave group](#) methods to efficiently predict [extreme events](#). Future work aims to develop generalized, condition-agnostic models.
- **Brown & Ppiras (2023):** Developed a [multi-fidelity approach](#) for [extreme event](#) prediction, combining different data sources for improved accuracy.
- **Wandji (2022):** Applied [extrapolation methods \(fitted distribution, wave height\)](#) to [dynamic stability events](#), effective with some assumptions for nonlinear processes.

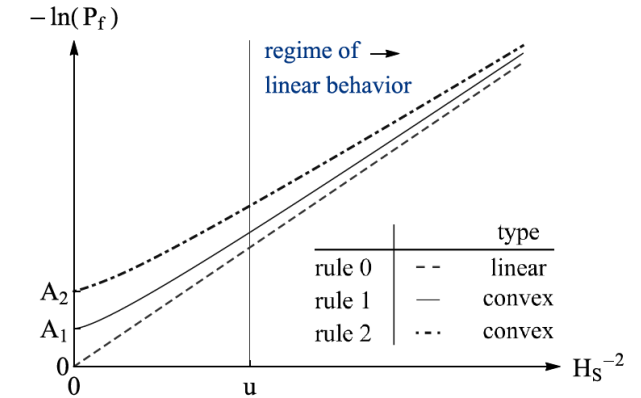


Fig. 1. Dependence of P_f on $1/H_s^2$ according to rules 0, 1 and 2 (schematically).

Anastopoulos & Spyrou (2023)

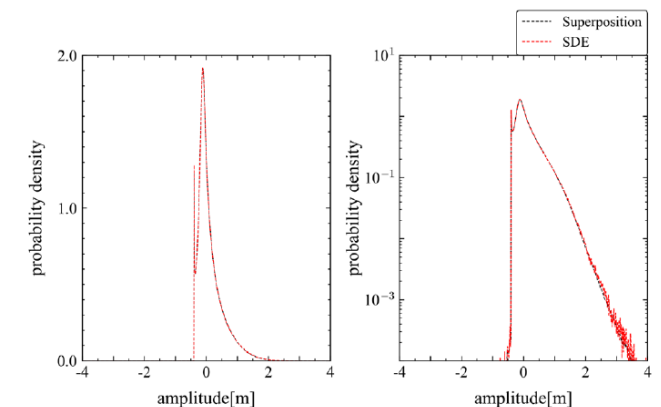


Figure 3: Comparison of GM variation's PDF between the superposition principle and result obtained by solving SDE, sea state with $T_{01}=7.987[s]$ and $H_{1/3}=7.5[m]$, subject ship ITTCship A1.

Maruyama et al. (2022)

Advances in Experimental Studies and Numerical Methods for Ship Stability

Efficient Numerical Methods:

- **Weems et al. (2022)**: Developed **reduced-order models for hydrodynamic predictions** using dimensionality reduction and active sampling. Highlighted the importance of uncertainty quantification to ensure model reliability.
- **Kim et al. (2023)**: Introduced a **regression-based method to approximate diffraction and radiation forces**, enhancing computational efficiency in ship motion models without losing accuracy.

Numerical and Theoretical Developments :

- **Lu & Gu (2023)**: Developed a **unified model to predict surf-riding and broaching** in stern quartering waves, focusing on refining parameters for better accuracy.
- **Dostal et al. (2023)**: Developed a **new approach for predicting the time it takes for a ship's roll to reach critical thresholds**, improving dynamic stability analysis in short-crested seas.

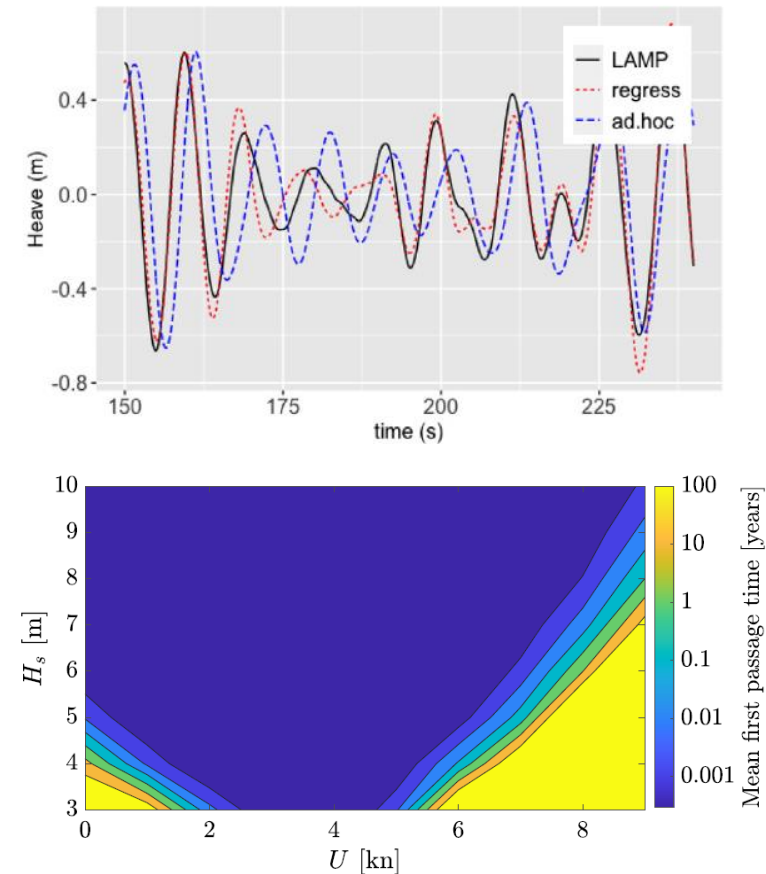


Fig. 7. Full mean first-passage times of roll amplitude $\varphi_c = 30^\circ$ for wave encounter angle $\chi_0 = 5^\circ$, ship speed U , and JONSWAP sea state with significant wave height H_s and

Dostal et al. (2023)

Updated ITTC Recommended Procedures

7.5-02-01-08	Significant Amplitude and Confidence Intervals for Stochastic Processes	Evaluation of variance of the mean and variance of the variance estimate, example has been updated (as TOR 3)
7.5-02-07-04.1	Model Tests on Intact Stability	References has been added
7.5-02-07-04.3	Predicting the Occurrence and Magnitude of Parametric Rolling	References has been added, primarily from the SGISC
7.5-02-07-04.4	Simulation of Capsize Behavior of Damaged Ships in Irregular Beam Seas	The latest international benchmark study on simulation of flooding and motions of damaged vessels was added. New sections on real time flooding risk evaluation and machine learning/artificial Intelligence methodologies have been added.
7.5-02-07-04.5	Estimation of Roll Damping	Equations were corrected, references has been added
7.5-02-07-04.6	Extrapolation for Direct Stability Assessment in Waves	Extrapolation over wave height has been added, example has been updated
7.5-02-07-04.7	Inclining Tests	Detailed description of wind effects and uncertainty analysis have been added

Reviewed ITTC Recommended Procedures – no update deemed necessary

Number	Title
7.5-02-01-01	Guide to the Expression of Uncertainty in Experimental Hydrodynamics
7.5-02-01-07	Guideline to Practical Implementation of Uncertainty Analysis
7.5-02-05-07	Dynamic Instability Tests
7.5-02-07-02.3	Experiments on Rarely Occurring Events
7.5-02-07-04.2	Model Tests on Damage Stability in Waves
7.5-03-01-01	Uncertainty Analysis in CFD Verification and Validation, Methodology and Procedures
7.5-03-02-03	Model Tests on Damage Stability in Waves

In fulfillment of item 2B of the Terms of Reference, identifies the following two procedures to be developed in support of Direct Stability Assessment within the framework of the second generation intact stability criteria:

1. Evaluation of Dynamical Characteristics of a Ship

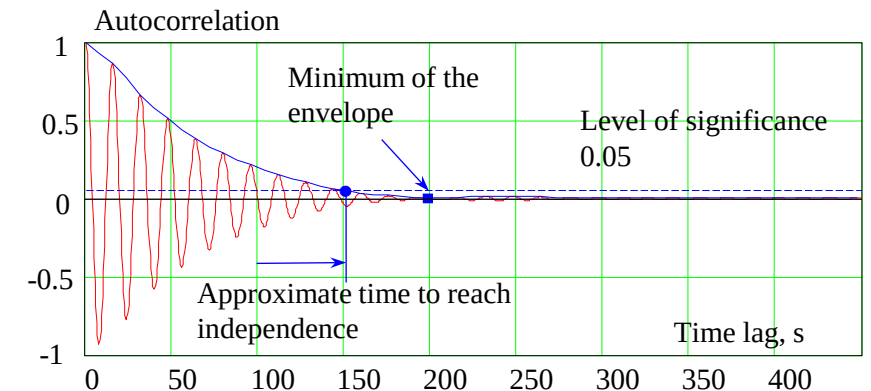
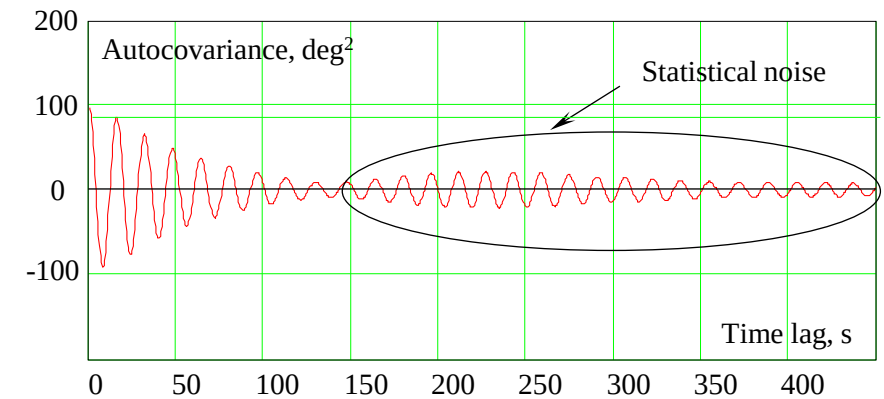
- Backbone curve
- Response curve
- Surf-riding equilibrium
- Heel during turn
- Turn in calm water
- Straight captive run in stern quartering waves
- Heel caused by drift and wind

2. Extrapolation Methods, not Covered by ITTC Recommended Procedures

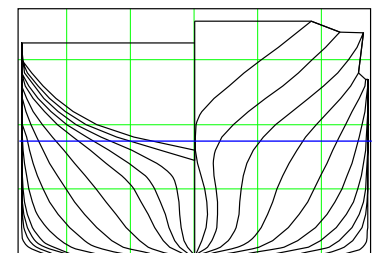
- Critical wave method
- Linear superposition method for excessive accelerations failure mode

- Update ITTC Procedure 7.5-02-01-08, titled “Single Significant Amplitude and Confidence Intervals for Stochastic Processes” when new information becomes available.
- New information did become available the procedure was updated as follows
 - Evaluation of the “cut-off” point
 - Text was restructured into three major sections: uncertainty of mean and variance, uncertainty of SSA, construction of confidence interval
 - Easy-to implement self-normalization method has been added
 - Example of application has been updated to reflect the changes

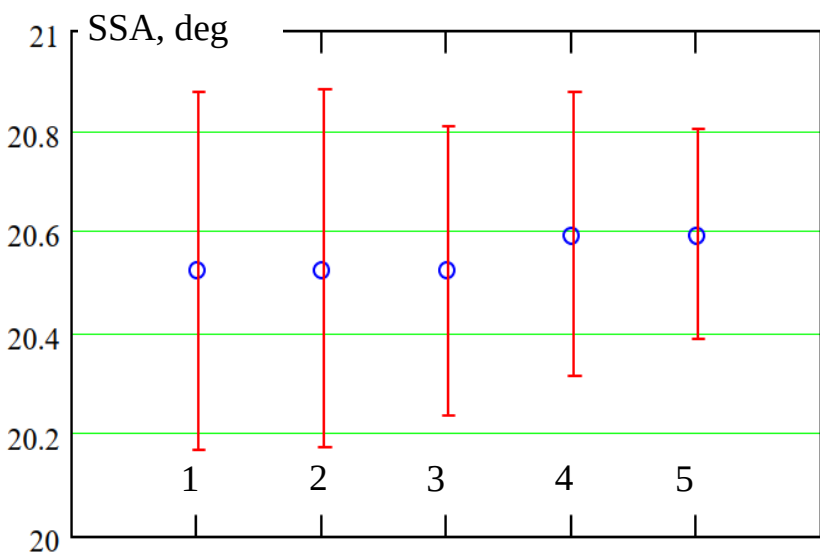
- Objective of the procedure: is to formulate the process for characterizing the uncertainty for data resulting from a stochastic process, such as ship motion data collected at either numerical simulation, model test or full scale trials.
- Estimates covered: mean, variance, SSA
- Three methods: large number of records (>30), any number of records and self-normalization
- Two methods for SSA: through variance and as a mean of 1/3 of the largest peaks
- Cut-off point issue (small number of records only):
 - Record of a stochastic process contains dependent points
 - This dependence affects width of the confidence interval
 - Autocorrelation/ autocovariance function is estimated to account for dependence
 - Estimate of autocovariance function may contain some “statistical noise” and need to be post-processed to remove it



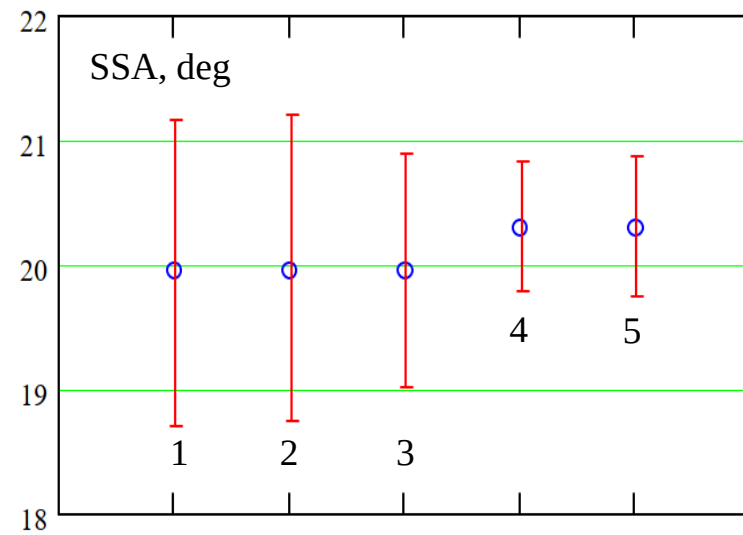
Example : simulated roll motion of ITTC A1 Ship (150 m long Containership)



Large number of records: 31 record 20.7 hrs.



Any number of records: 7 record 4.7 hrs.



SSA estimated through variance: (1) "Boundary" method (2) Delta method (3) Self-normalization

SSA by peak counting: (4) Normal distribution (5) Self-normalization

- To develop new ITTC recommended procedures in support of direct stability assessment within the 2nd generation IMO intact stability criteria.
- Direct Stability Assessment uses the latest numerical simulation technology to ensure both existing and future fleet has sufficient stability in waves.
- Overall objective is to facilitate member organizations to provide services related to direct stability assessment.
- Three new ITTC procedures have been developed:
 - Avoiding self-repeating effect in time-domain numerical simulation of ships motions (QSG suggested number 7.5-02-01-09)
 - Estimation of Frequency of Random Events by Direct Counting (QSG suggested number 7.5-02-01-10)
 - Statistical Validation of Extrapolation Methods for Time Domain Numerical Simulation of Ship Motions (QSG suggested number 7.5-02-01-11)

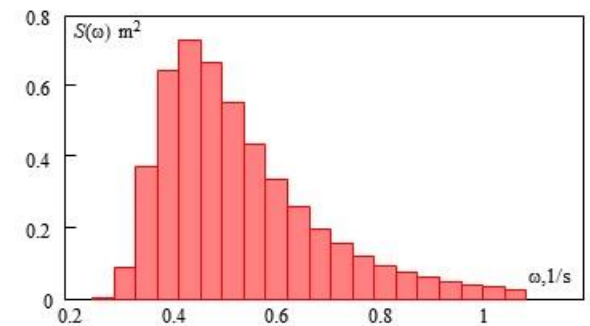
- Objective of New Procedure:
 - Provides guidelines for verifying the absence of the self-repeating effect in time-domain numerical simulations of irregular waves.
 - Ensures statistical validity in direct stability assessments, as referenced in sections 3.3.2.1 of the Interim Guidelines and Explanatory Notes (MSC.1/Circ. 1627).
- Wave Elevation and Auto-correlation function:
 - Irregular wave time series, ζ_W , is constructed by superimposing N regular wave components.

$$\zeta_W(t) = \sum_{i=1}^N A_i \cos(\omega_i t + \varphi_i)$$

- The self-repeating effect occurs when the auto-correlation function, r , shows patterns indicating dependence in the wave time series, which should represent a stochastic process.

$$r(\tau_j) = V^{-1} \sum_{i=1}^N S(\omega_i) \cos(\omega_i \tau_j)$$

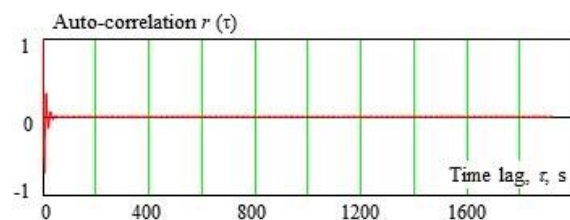
S : wave spectrum,
 V : variance of wave elevations



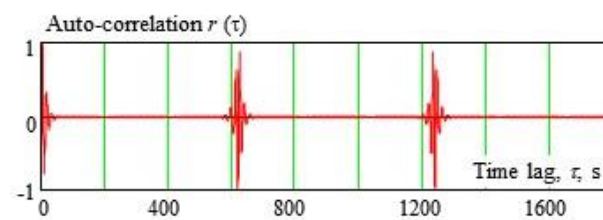
Discretization of wave spectrum

Detection of Self-Repeating Effect

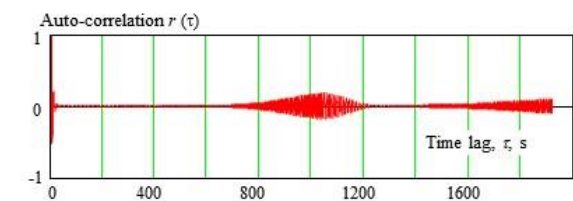
- Auto-Correlation Analysis:
 - The auto-correlation function, r , is used to detect the presence of self-repeating effects.
 - A "clean" r function shows no increase after initial decay, indicating no self-repeating effect.
 - If τ increases beyond a threshold, the wave model exhibits self-repeating effect.
- Practical Application:
 - For uniform frequency distributions, the valid duration of the record is limited by the onset of spikes in r .
 - For non-uniform distributions, the envelope of the auto-correlation function helps identify the point where the signal starts increasing.
 - This analysis helps determine the valid time span of numerical simulations, ensuring the accuracy of ship motion models.



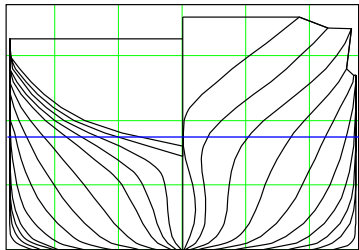
Auto-correlation without self-repeating effect



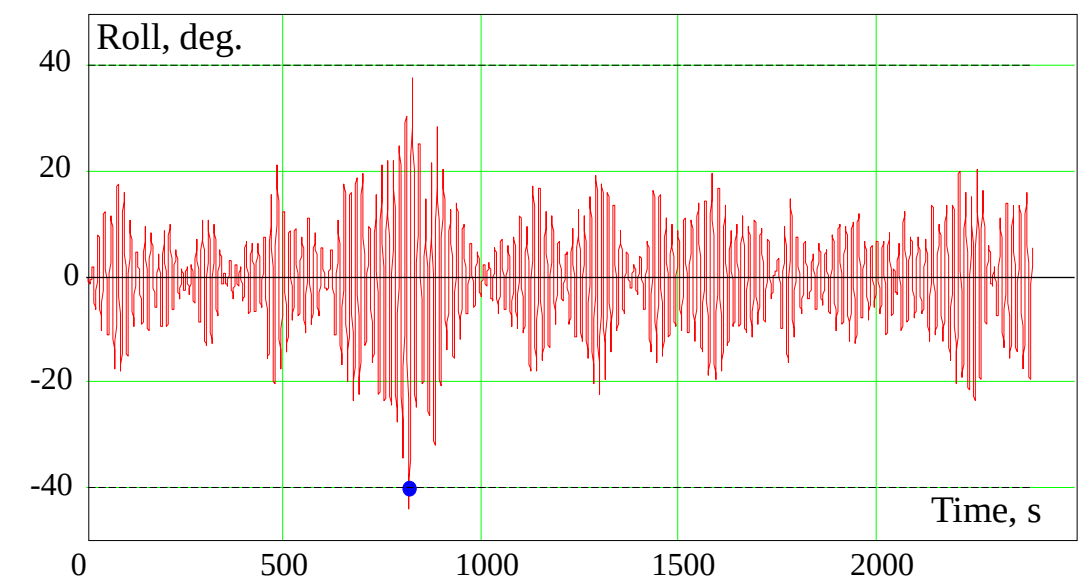
Auto-correlation with self-repeating effect
(left: uniform, right: non-uniform frequency distribution)



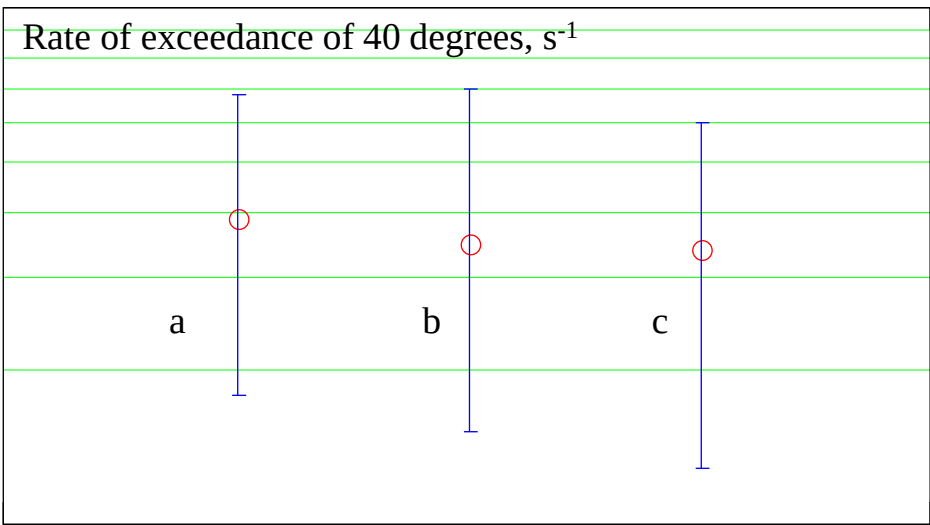
- Objective is to estimate statistical frequency of random events from time series. It identified in IMO documents as “Direct Counting”
- Following Explanatory Notes for the Second Generation Intact Stability Criteria, three methods are included:
 - Method based on exponential distribution applicable when the simulation stops when event is encountered
 - Method based on probability estimation applicable for the set of the records of the same length
 - Method based on binomial distribution applicable for records of different lengths; each record may contain any number of events
- All the methods come with uncertainty quantification in form of a confidence interval
- QSG suggested number 7.5-02-01-10



Example : simulated roll motion of ITTC A1 Ship (150 m long Containership)
Event to count exceedance of ± 40 degrees



$1 \cdot 10^{-4}$



$1 \cdot 10^{-5}$

- a - method based on exponential distribution
- b - method based on probability estimation
- c - method based on binomial distribution

Purpose: describe a process for the validation of extrapolation methods used for DSA.

The validation is considered successful if an extrapolation method (e.g. 7.5-02-07-04.6: *Extrapolation for Direct Stability Assessment in Waves*) **captures a “true” value**. The percentage of these “successes” should be about accepted confidence probability.

Formulation of the procedure and the acceptance criteria for validation based on the work of Smith (2019), i.e., the three-tier validation:

- Tier 1: single extrapolation
- Tier 2: single condition
- Tier 3: multiple conditions.

The validation of the extrapolation is assessed by means of the confidence intervals of the “true” and the “extrapolated estimate”.

QSG suggested number 7.5-02-01-11

Tier 1 validation (single extrapolation):
Bernoulli trial, where success (overlap of confidence intervals) is attributed 1.0 and failure (no overlap of the confidence intervals) is given 0.0.

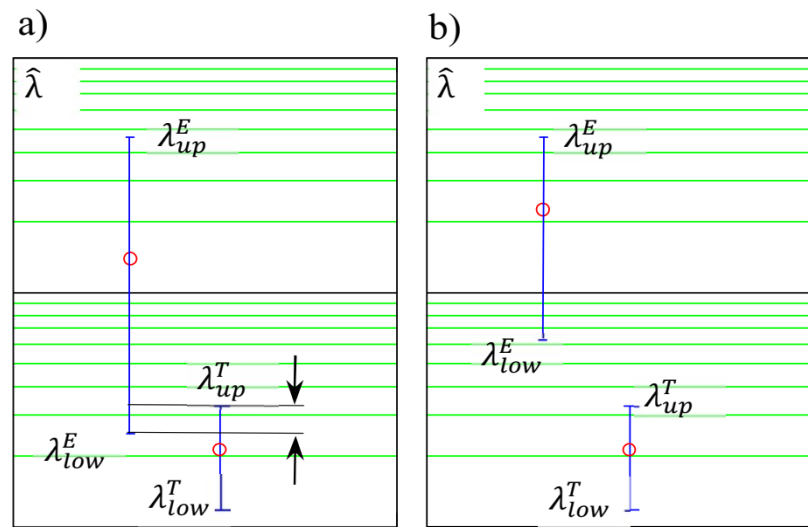


Figure 1: Tier 1 validation (a) success (b) failure

Tier 2 validation (single condition – multiple extrapolations): computed through binomial quantiles, where 0.88 was suggested as the standard for passing rate (as in the IMO Interim Guidelines).

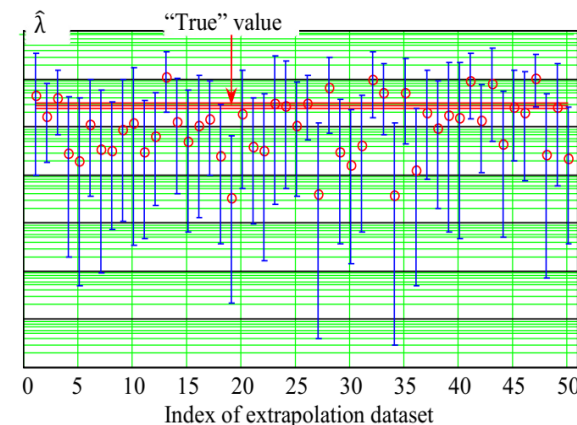


Figure 2: Tier 2 Validation: Success. Passing rate 0.9, with the tier 1 failures on datasets 19, 27, 30, 34 and 36.

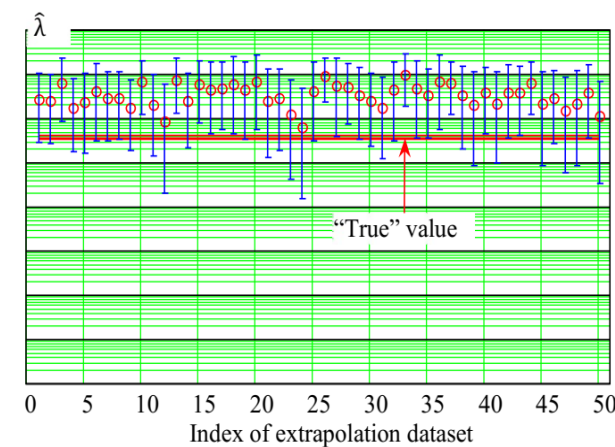


Figure 3; Tier 2 Validation: Failure. Passing rate 0.68.

Tier 3 validation (multiple conditions):

Account for different ship speeds, relative wave headings and sea states.

Accepts/rejects an extrapolation method or define limitations for it, for a particular specific intended use.

An assumption allowance is suggested to be introduced in the lower limit of the tier 2 criterion.

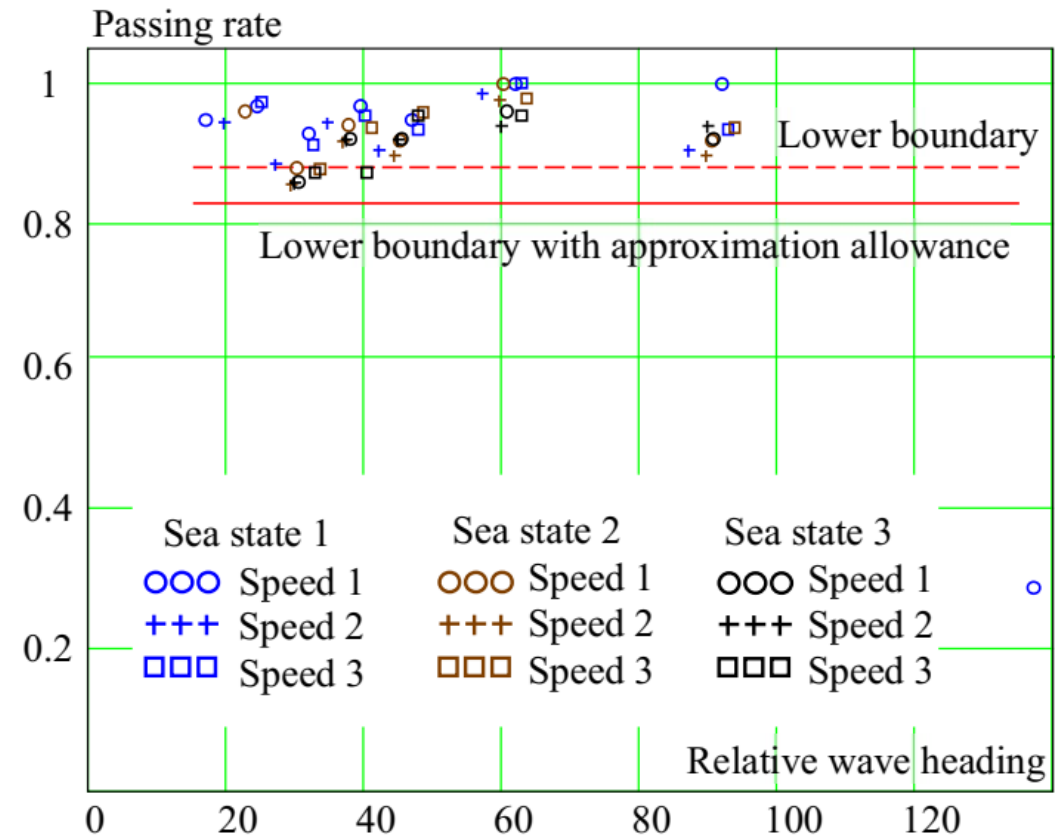


Figure 4: Notional tier 3 validation

Appendix: Example of **partial validation** of EPOT extrapolation method based on data from Campbell et al. (2023). The validation is partial as the scope is limited by a single sea state and speed.

Input data

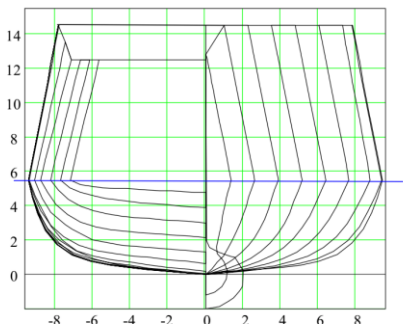


Figure A1: ONR tumblehome topside configuration

Table A2: Validation simulation campaign

Headings deg	Total time, h	Largest target
15	285,000	20
22.5	100,000	27.5
30	100,000	45
37.5	100,000	60
45	345,000	70
60	300,000	70
90	345,000	37.5
135	345,000	20

Extrapolation

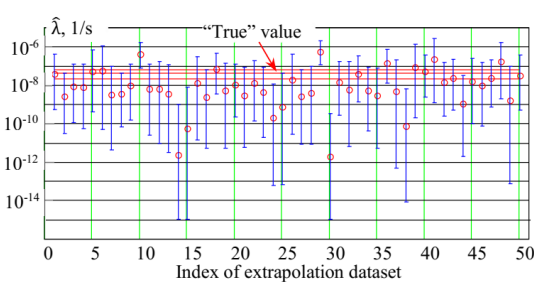


Figure A2: Heading 30 deg, passing rate 0.86

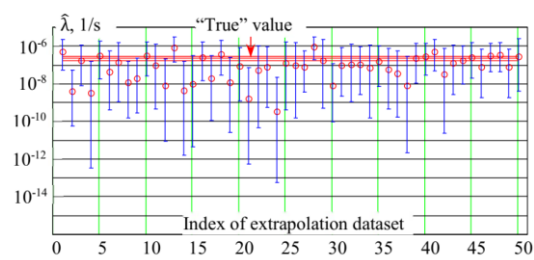


Figure A3: Heading 37.5 deg, passing rate 0.86

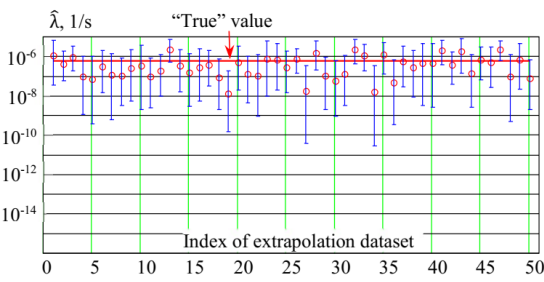


Figure A4: Heading 45 deg, passing rate 0.94

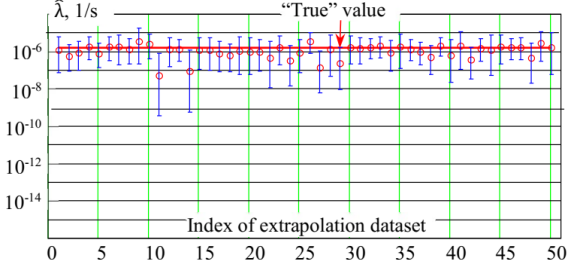


Figure A5: Heading 60 deg, passing rate 0.94

Validation

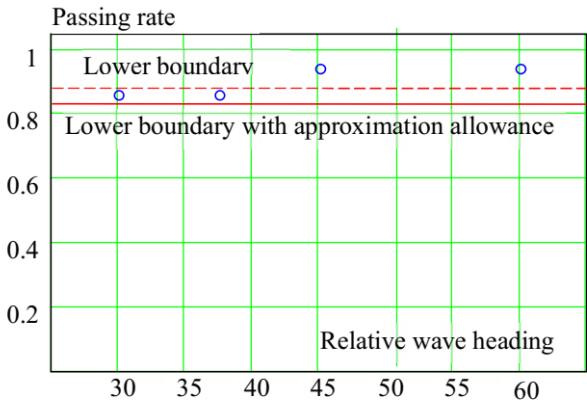


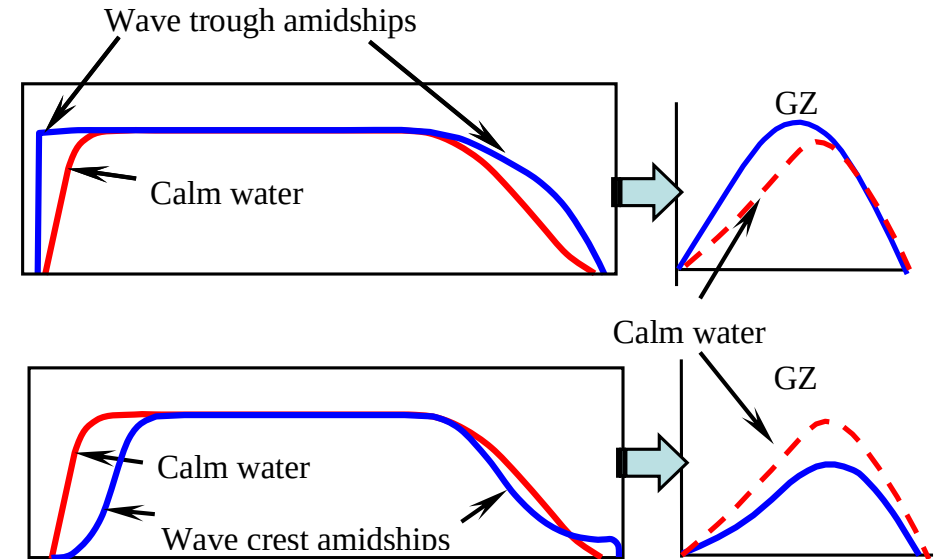
Figure A6: Partial tier 3 (multiple conditions) validation of EPOT for 40 degrees exceedance rate

Historical Background

The roll righting arm (GZ) curve in waves is an important factor in the evolution of ship's changing stability in waves. For more than a century, naval architects have been aware of the phenomenon of transverse stability change in longitudinal waves.

Physical Background and Motivation

For ships with significant variation of a shape of the waterplane, the change of GZ in waves can be particularly noticeable. The waterplane area has a substantial effect on ship stability, which is well known from ship hydrostatic. When the waterplane area is reduced, so is the GZ.



Large roll excursions may be better understood if evolution of the shape of the instantaneous GZ curve in irregular waves is known.

Calculation Procedure:

Most commercially available hydrostatic programs compute the restoring arm as a quasi-static wave-pass problem, evaluating only the variation in Froude-Krylov and hydrostatic forces.

In righting arm calculations, **heel rotation disturbs the ship's static or dynamic equilibrium** in pitch and heave, changing the heave force and pitch moment. These changes can affect the roll moment and need to be excluded from the analysis.

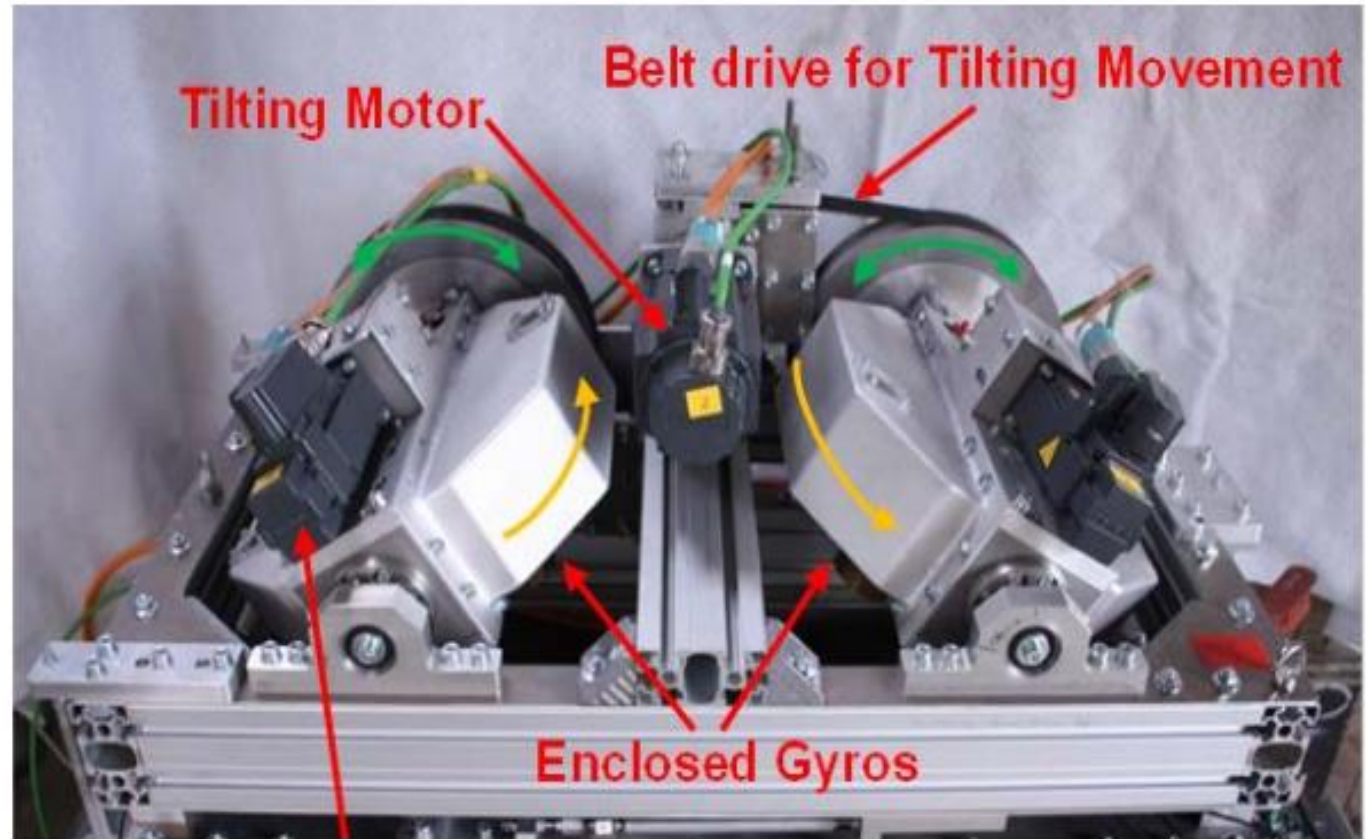
To perform the **instantaneous GZ curve calculation in irregular waves** alongside time-domain numerical simulations for a selected time interval, follow these steps:

1. **The ship is heeled through a range of angles relative to its instantaneous position.**
2. **Forces and moments acting on the ship are computed for each heel angle.**
3. **The ship's heave position and pitch angle are iteratively adjusted relative to a global coordinate system until dynamic equilibrium is achieved.**
4. **The net roll moment determines the instantaneous GZ value for the current heel angle.**

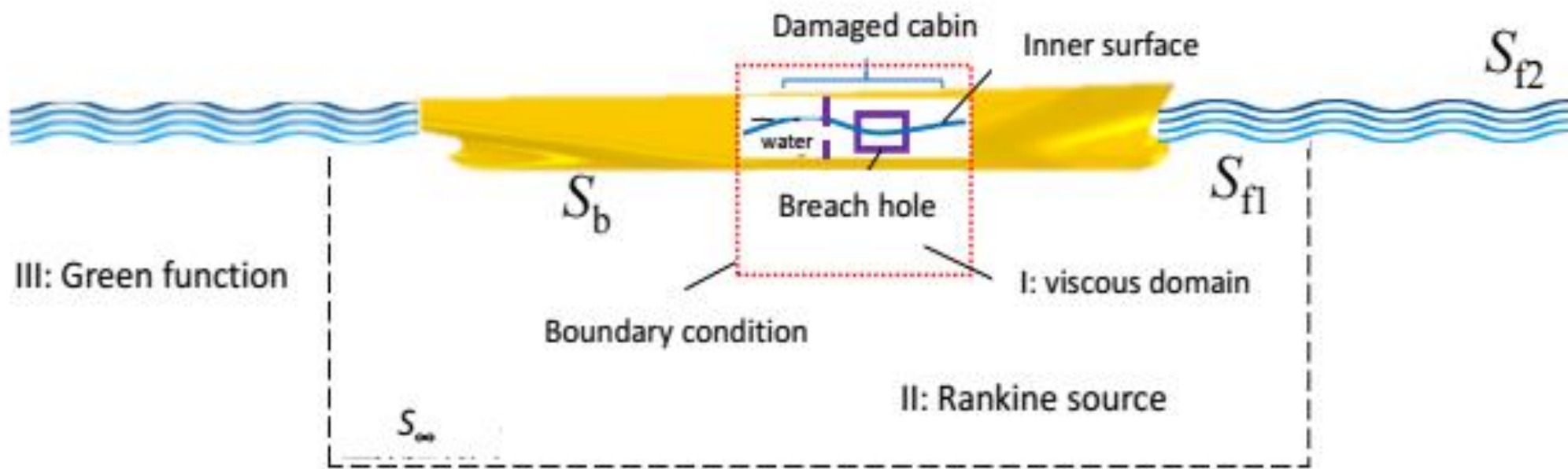
This calculation procedure is detailed in the **draft ITTC recommended procedure** 'Computational procedure for instantaneous GZ curve during time-domain numerical simulation in irregular wave.

QSG suggested number 7.5-02-07-04.8

Valanto and Schumacher (2021) investigate the roll damping of intact ship with varying draughts and heeling angles to study the effect of the ship floating position on these coefficients. Then further study the roll damping of damages ship with different damaged cases was conducted. The roll excitation is generated by a gyroscopic machine using gyroscopic controlled by a dedicated software



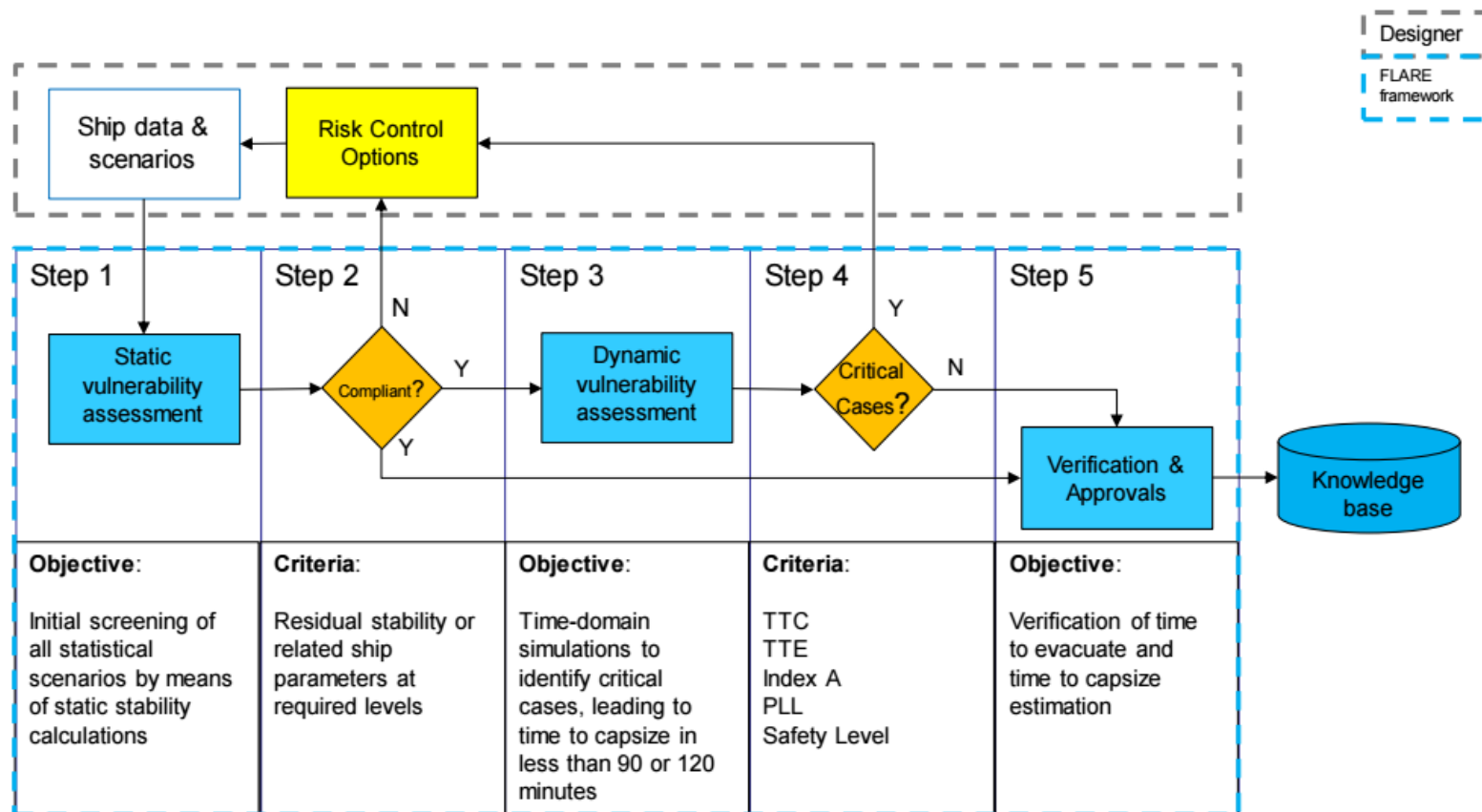
Bu et al. (2021) describe a viscous and potential prediction method for damaged ship motion. The method combines floodwater and motion in waves for the definition of the two domains. The 3D time-domain potential method is coupled with CFD method.



Objective: to investigate the current state of the art on flooding dynamics of damaged ship in waves, including model test and CFD



There were new developments in the H2020 FLARE project, especially the quantitative risk models pertaining to ship flooding. A new risk-based method for the direct assessment of flooding risk estimation using numerical tools was proposed with support from datasets. Efforts has been made to build more suitable model for cruise ships than current high level risk models (Vassalos, et al. 2021)



Described earlier in the presentation:

- FLARE – benchmark data
- CG Curve data provided by CSSRC
- Parametric Roll Kapsenberg et al. (2020)

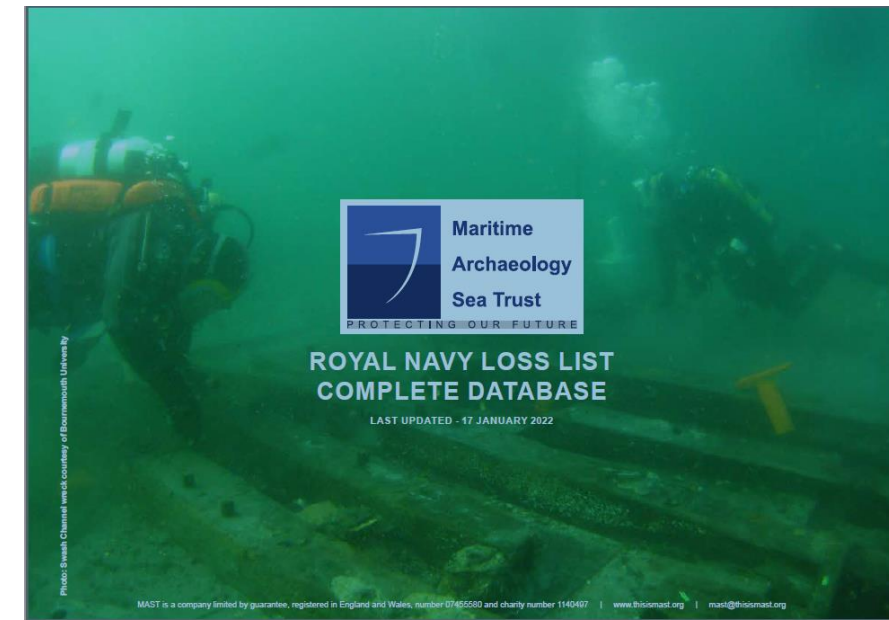
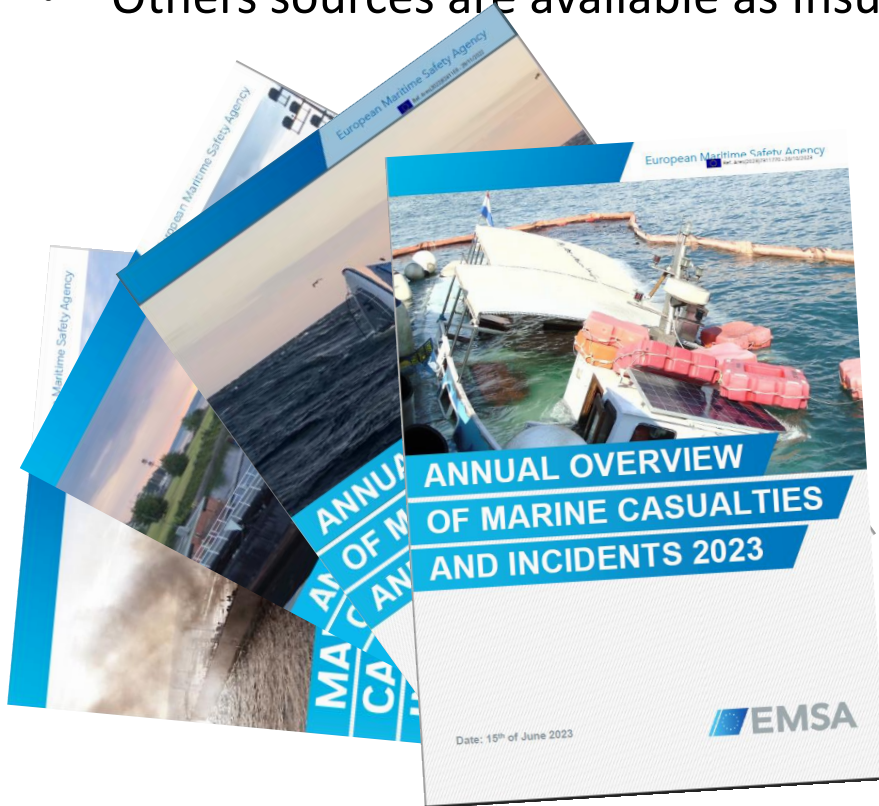


FLARE
FLOODING ACCIDENT RESPONSE

<http://www.shipstab.org/index.php/news/98-added-flare-benchmark-study-damaged-cruise-ship>

Accident investigation

- Data from marine casualties: e.g. EMSA and national investigative bodies in the EU
- Others sources are available as Insurance company or even Archeology database



- Literature survey has been conducted including books, journals and conference proceedings
- Highlights of reporting period:
 - Publication of the Second Generation Intact Stability Criteria by IMO; three new procedures were developed to support trial application of the Direct Stability Assessment and one existing procedure was updated
 - Publication of the book “Contemporary Ideas on Ship Stability – from Dynamics to Criteria”; review of the book is included in the Report
 - Publication of virtual special issue of Ocean Engineering “Extreme Stochastic Dynamics of Ships”; review of relevant papers was including in the Report
 - One of the papers of this Special Issue contained information for updating procedure 7.5-02-01-08 Single Significant Amplitude and Confidence Intervals for Stochastic Processes

Adopt updated procedures:

- 7.5-02-01-08 “Single Significant Amplitude and Confidence Intervals for Stochastic Processes”
- 7.5-02-07-04.1 “Model Tests on Intact Stability”
- 7.5-02-07-04.3 “Predicting the Occurrence and Magnitude of Parametric Rolling”.
- 7.5-02-07-04.4 “Simulation of Capsize Behavior of Damaged Ships in Irregular Beam Seas”
- 7.5-02-07-04.5 “Estimation of Roll Damping”
- 7.5-02-07-04.6 “Extrapolation for Direct Stability Assessment in Waves”
- 7.5-02-07-04.7 “Inclining Tests”

Adopt new procedures (numbers per QSG suggestion):

- 7.5-02-01-09 “Avoiding self-repeating effect in time-domain numerical simulation of ship motions”
- 7.5-02-01-10 “Frequency of Random Events”
- 7.5-02-01-11 “Statistical Validation of Extrapolation Methods for Time Domain Numerical Simulation of Ship Motions”
- 7.5-02-07-04.8 “Computational Procedure for Instantaneous GZ Curve during Time-domain Numerical Simulation in Irregular Wave”

Develop new procedure to support application of Direct Stability Assessment within the framework of the Second-Generation Intact Stability Criteria:

- “Evaluation of Dynamical Characteristics of a Ship”

Further update procedure 7.5-02-07-04.6 “Extrapolation for Direct Stability Assessment in Waves” to include two more extreapolation methods:

- Critical Wave Method
- Linear Superposition Method