National Technical University of Athens
School of Naval Architecture & Marine Engineering

SAFEDOR

PREDICTION OF CAPSIZE PROBABILITY

K.J. SPYROU

Open Workshop on Risk-Based Approaches in the Maritime Industry
NMRI, Tokyo, 22-23 May 2007

Related SAFEDOR Tasks:
- Environmental data
- Probabilistic assessment of intact stability
- Implementation

Objective:

To develop a method that:

- has a scientific basis and is capable to address individually all known types of ship instability,
- can exploit the state-of-the-art of sea wave statistics and models,
- is not biased towards a single type modeller of ship motions,
- is easily integrated within a risk assessment framework.
- practicality is demonstrable.

Key observations driving the approach:

- "Near regularity" of (wave) excitation is conducive to large response.
- Ship instabilities are either:
  - manifestations of resonant behaviour (thus entailing some regularity in the excitation).
  - outcome of a single critical encounter.
  - cumulative effect of random waves.
- Higher waves tend to appear in **groups**.

Background

waves

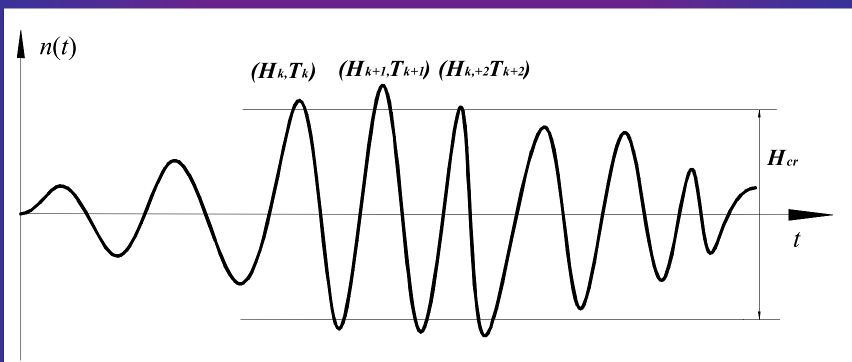
- **Draper (1971)**
- **Kimura (1980)**
- **Wist, Myrhaug & Rue (2004)**

ship

- **Tikka & Paulling (1990)**
- **Myrhaug, Dahle, Rue & Slaatelid (1999)**

Wave group: A sequence of waves with heights that exceed a certain preset level and nearly equal periods.

(e.g. Masson & Chandler, 1993; Ochi, 1998)



$$T_k, T_{k+1}, T_{k+2} \in [T, T+\delta T] \text{ and } H_k, H_{k+1}, H_{k+2} \geq H_{cr}$$ (run length = 3)

Run length: number of consecutive waves exceeding the preset level

Combining the strengths of deterministic and probabilistic viewpoints

Concept:

The probability of occurrence of a certain type of instability is equal to the probability of encountering the critical (or "worse") wave group that generates the instability.

Key approximation:

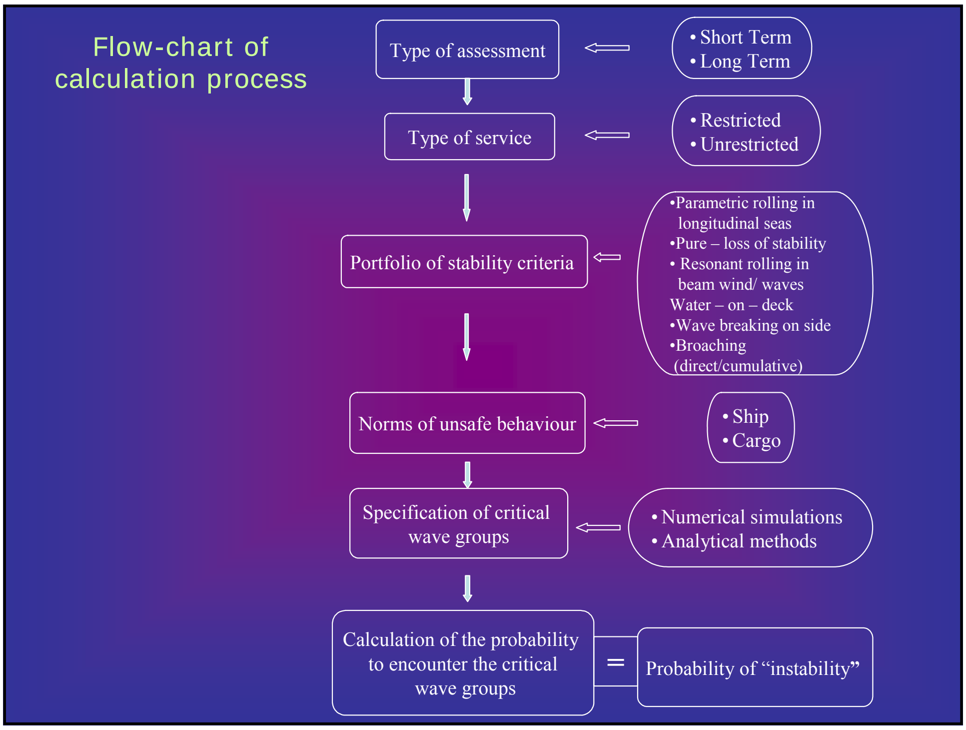
Problem disassembled in two parts:

Dynamics (deterministic) part

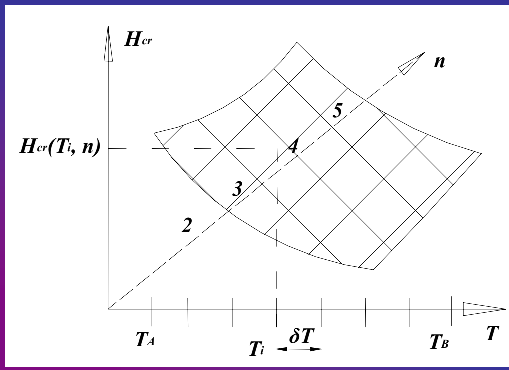
Determine specification of critical wave groups from ship motions dynamics.

Wave (probabilistic) part

Determine probability of encounter of such wave groups from sea wave statistical models.



Procedure for determining critical wave groups.



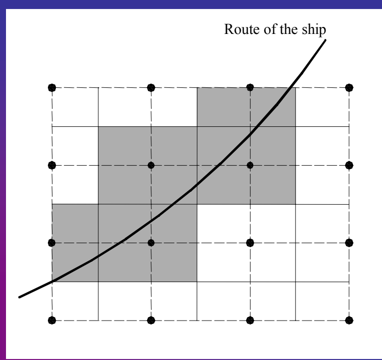
- Discretise sea wave period range.
- Take period T_i
- Take n waves in group.
- Calculate the corresponding critical wave height $H_{cr}(T_i, n)$ from ship dynamics.
- Continue for $n+1$ waves in group.
- Take next wave period $T_{i+1}=T_i+\delta T$ until whole range is spanned.

Distribution of “weather nodes” along route or in wider area of navigation.

Each node represents a sea-state that holds for the rectangle around the node.

Probabilities are calculated per node.

Weighted sums (according to time spent in vicinity of node) produce the overall probability figure.



Assumptions:

Gaussian waves defining a stationary ergodic random process.

Wave spectral density ‘narrow banded’.

$$P = P_1 \cdot P_2$$

$$P_1 = P\left[T_1, T_2, \ldots, T_k / H_n > H_{cr}\right] = \underbrace{\int_{\tau_i}^{\tau_j}\int \ldots \int_{\tau_i}^{\tau_j}}_{k} f\left(\boldsymbol{\tau}/h_n > h_{cr}\right) d\tau, \quad \mathrm{n} = 1, \ldots, k$$

$$P_2 = P\left[H_n > H_{cr}\right] = \int_{h_n}^{\infty} f(h)\, dh$$

$$\text{where } \boldsymbol{\tau} = \left[\frac{T_1}{T_{mean}}, \ldots, \frac{T_k}{T_{mean}}\right]^T \text{ and } \tau_i = \frac{T_i}{T_{mean}}, \ \tau_j = \frac{T_j}{T_{mean}}, \ h_n = \frac{H_n}{H_{rms}}$$

Adopted wave group theory

- Kimura theory with some modification is applied (spectral method).
- A sequence of wave heights is treated as Markov chain (nonzero correlation between consecutive waves only).

Conditional pdf of *n* successive wave periods given the wave height exceeds a threshold level (Wist, Myrhaug & Rue):

$$f_{\mathrm{T/H}}\left(\boldsymbol{\tau}/\mathbf{h}_i > h_{cr}\right) = \frac{e^{-\frac{1}{2}\left(\boldsymbol{\tau}-\boldsymbol{\mu}_{\tau/h_{cr}}\right)^T \Sigma^{-1}_{\tau/h_{cr}} \left(\boldsymbol{\tau}-\boldsymbol{\mu}_{\tau/h_{cr}}\right)}}{(2\pi)^{n/2}\left|\Sigma_{\tau/h_{cr}}\right|^{1/2}}$$

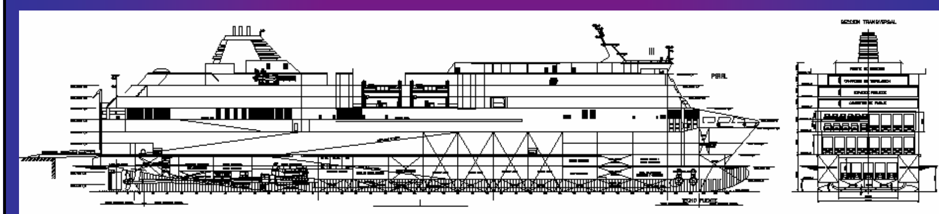
Marginal pdf for large wave heights (Tayfun):

$$f_h = \frac{h}{2[2\kappa(1+\kappa)]^{1/2}}\left(1+\frac{1-\kappa^2}{4\kappa h^2}\right)\exp\left(-\frac{h^2}{4(1+\kappa)}\right)$$

Application 1: Ropax ferry

Ship data provided by Navantia

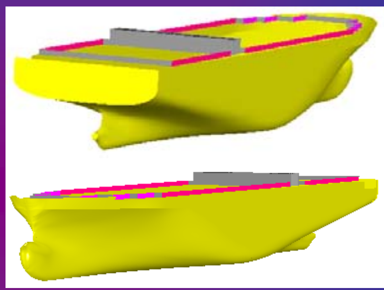
L_{bp} (length)	157 *m*	GM (metacentric height, corrected)	2.08 *m*
B (beam)	26.2 *m*	To (natural roll period)	15.26 *s*
D (depth, main deck)	9.20 *m*	b_{BK}, l_{BK} (breadth, length of bilge keels)	0.26 *m* 60.9 *m*
T (mean draft)	6.20 *m*	KG (vertical position of centre of gravity above keel)	12.724 *m*
C_b (block coef.)	0.626	Trailers	99
Vs	22.5 *kn*	Cars	166



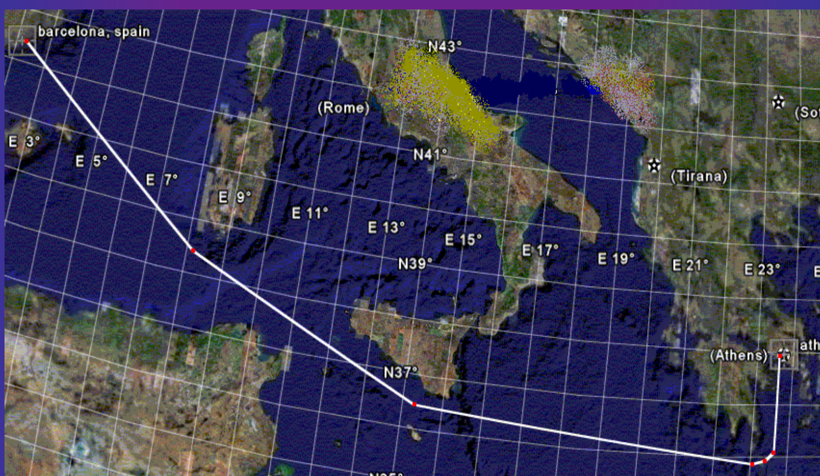
Application 2: Post – panamax containership

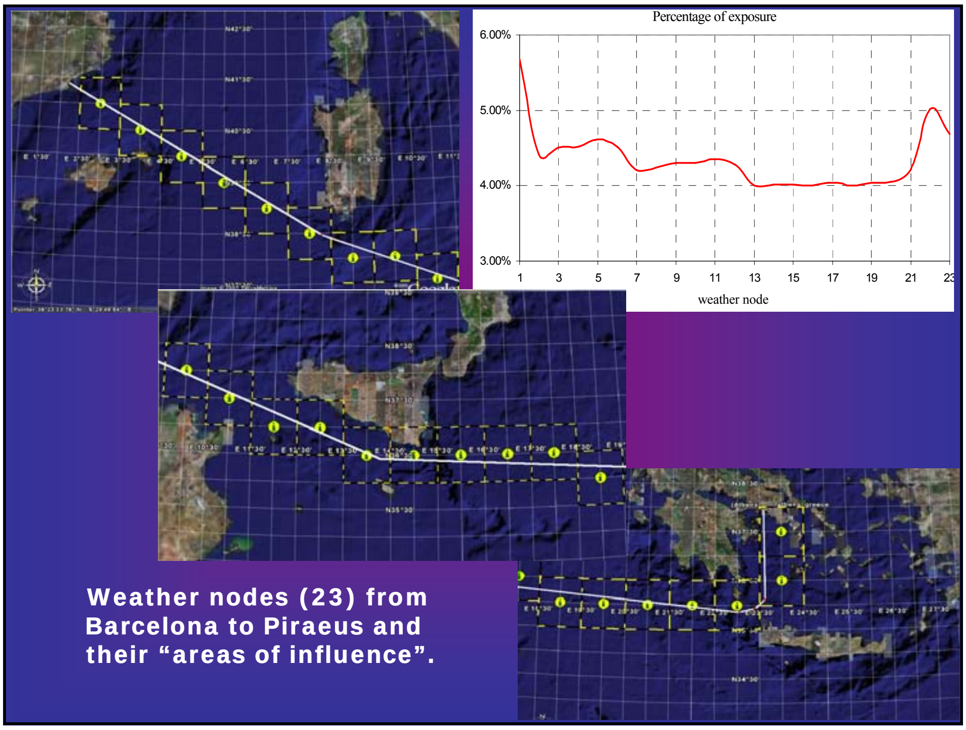
Ship provided by GL, courtesy of Aker Yards.

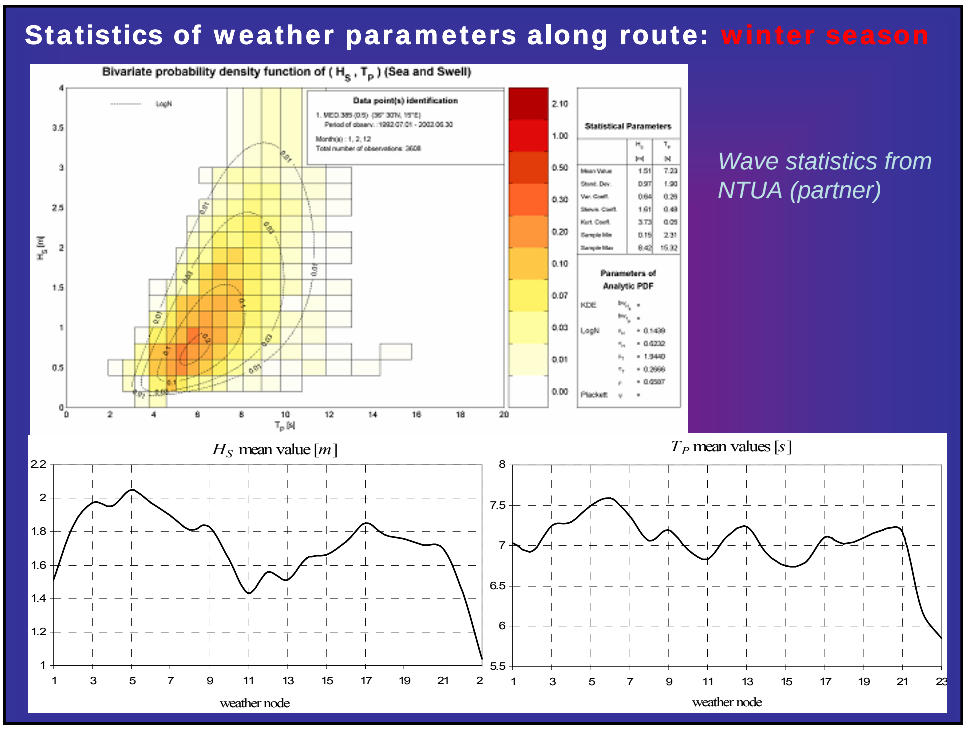
L_{bp} (length)	264.4 *m*	GM (metacentric height, corrected)	0.61 *m*
B (beam)	40 *m*	Vs	24 *kn*
D (depth, main deck)	24.3 *m*	To (calculated natural roll period – based on roll radius of gyration 0.381*B*)	39.12 *s*
T (mean draft)	13.97 *m*	KG (vertical position of centre of gravity above keel)	18.79 *m*
C_b (block coeff.)	0.6	number of TEUs	5048



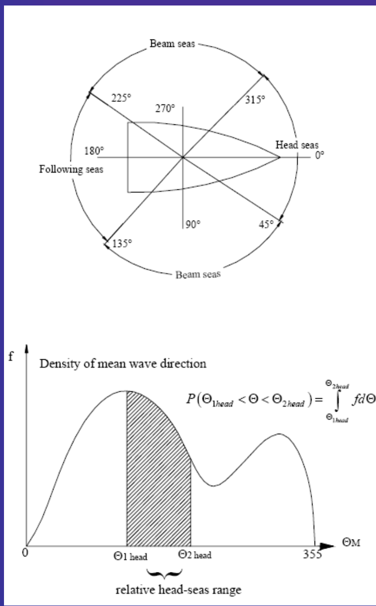
Ropax route: Barcelona – Piraeus (1209.30 n.m.)



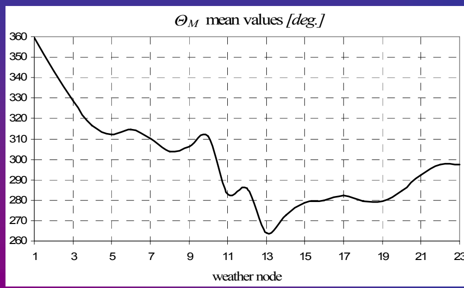

Percentage of exposure
weather node
Weather nodes (23) from Barcelona to Piraeus and their “areas of influence”.


Statistics of weather parameters along route: winter season
Bivariate probability density function of (Hs , Tp) (Sea and Swell)
Data point(s) identification
Statistical Parameters
Parameters of Analytic PDF
Wave statistics from NTUA (partner)
Hs mean value [m]
weather node
Tp mean values [s]
weather node

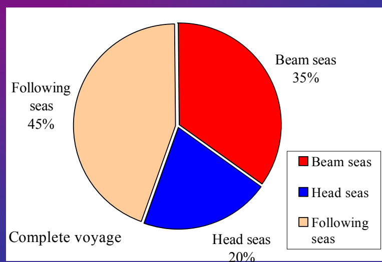
Convention of type of wave encounter
(0^0 waves coming from North, 90^0 East)



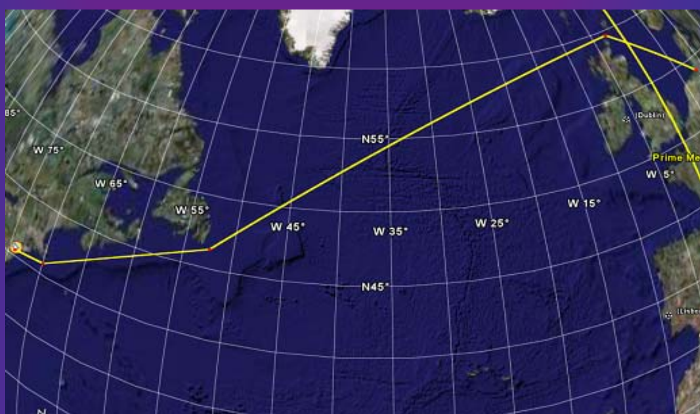
Mean wave direction per node

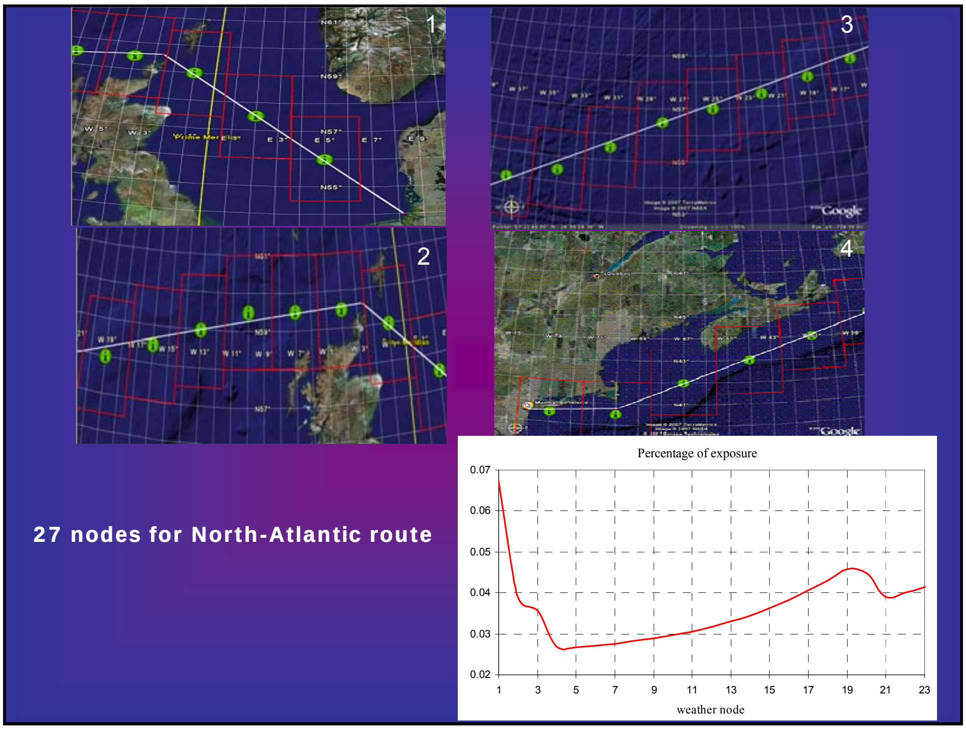


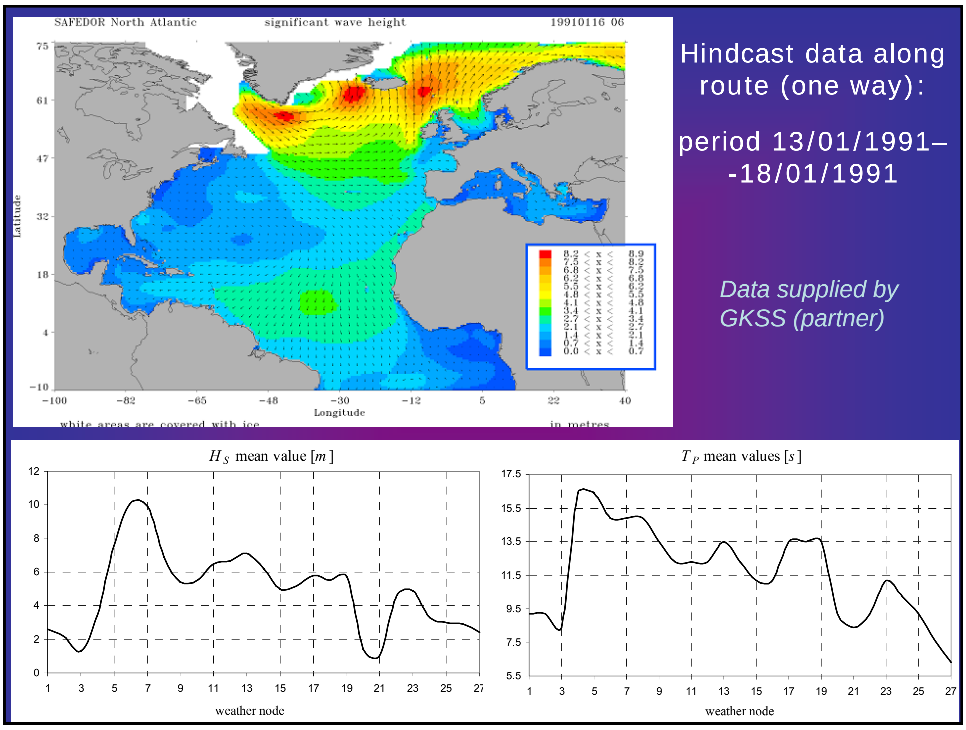
% in beam, head & following seas



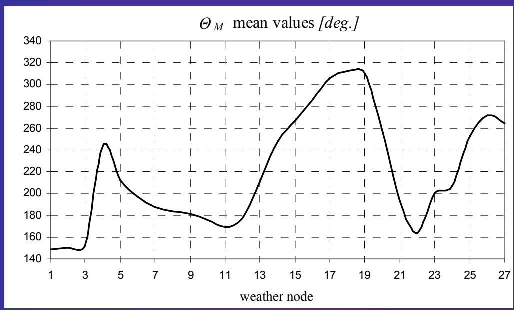
Containership route: Hamburg – New York (3422.86 n.m.)




1
2
3
4
27 nodes for North-Atlantic route
Percentage of exposure
0.07
0.06
0.05
0.04
0.03
0.02
1 3 5 7 9 11 13 15 17 19 21 23
weather node

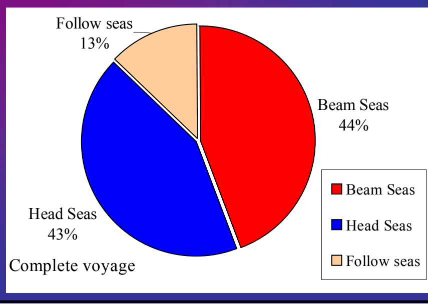

SAFEDOR North Atlantic
significant wave height
19910116 06
Latitude
Longitude
white areas are covered with ice
in metres
Hindcast data along route (one way):
period 13/01/1991–-18/01/1991
Data supplied by GKSS (partner)
H_S mean value $[m]$
weather node
T_P mean values $[s]$
weather node

Mean wave direction per node



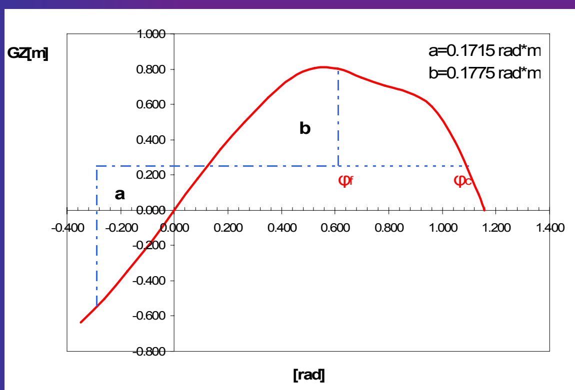
North-Atlantic route

% in beam, head & following seas



Safety limits of ROPAX

"Capsize" threshold → Critical inclination → Critical roll angle set according to the weather criterion, as the minor of:

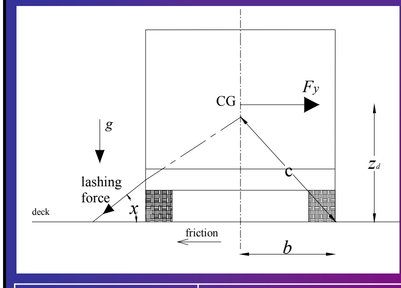


- the angle of vanishing stability (63^0)
- flooding of non-watertight openings (35^0)
- 50 deg

↓

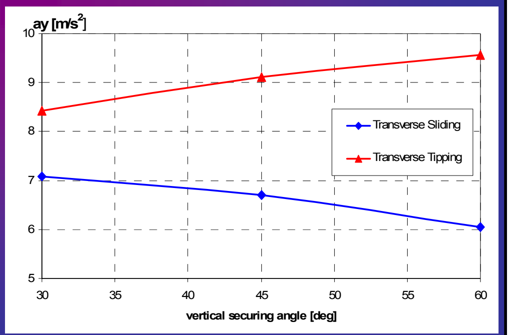
Critical roll angle 35 deg

Shift-of-cargo threshold → Critical transverse acceleration that could endanger the lashing of remotest trailer (against tipping and sliding) → Examination of lashing strength according to IMO's *Cargo Securing Manual*

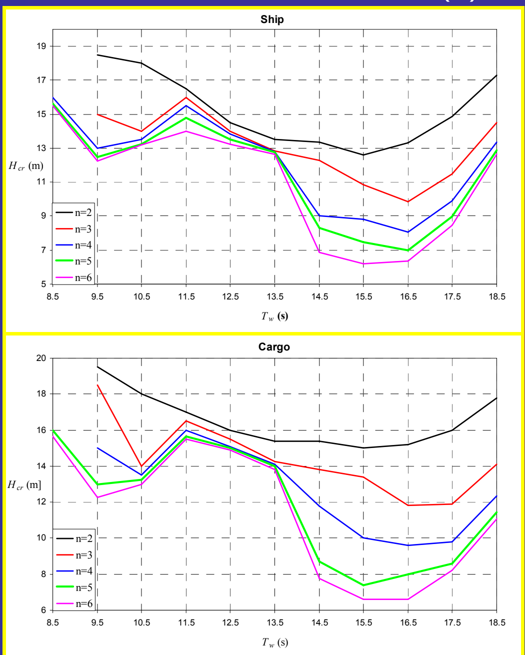


Critical transverse acceleration = 6.04 m/s²

cargo mass	*m* = 49 *t*
centre of gravity above deck	a = 2.36 *m*
lever-arm of tipping	b = 1.261 *m*
Coefficient of friction	Steel – rubber: μ = 0.3
lashing arrangement	3 chains with MSL = 100 *kN* on each side, symmetrical vertical securing angle: α = 30°/45°/60°



CRITICAL WAVE GROUPS (1): BEAM-SEA RESONANCE

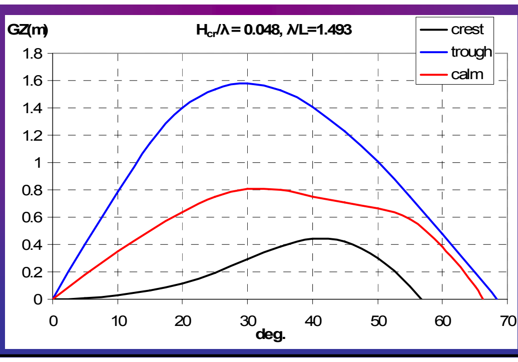


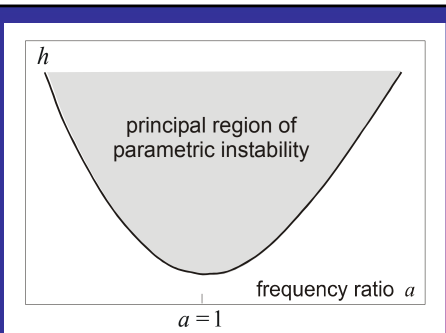
Employed ship dynamics tool:

Coupled roll, heave and sway simulation model (Themelis & Spyrou 2006).

- Ship assumed initially unbiased (no wind).
- Waves approach ship from 90^0
- Wave breaking limit taken into account.

CRITICAL WAVE GROUPS (2): HEAD-SEAS PARAMETRIC ROLLING





Key parameters:

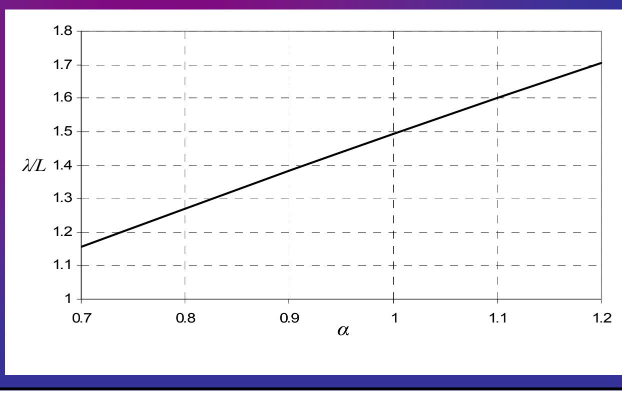
$$a = \frac{4\omega_0^2}{\omega_e^2}$$

ω_0 : natural roll frequency

ω_e : frequency of encounter

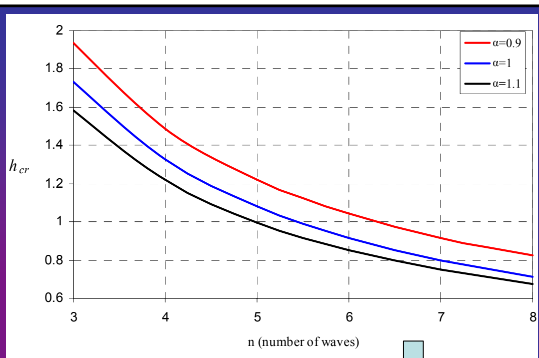
$h = f\,(GZ$ fluctuation on wave)

Given the speed, find eligible range of wave lengths.

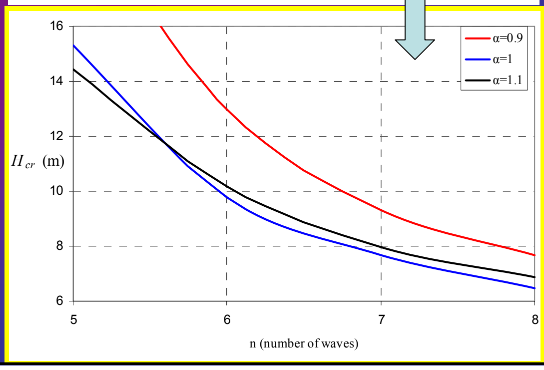


"Transient" criterion

$$h - \frac{4k}{\omega_0} = \frac{0.693 + \ln q}{1.571 p}$$



Critical wave heights, depending on number of waves in group:



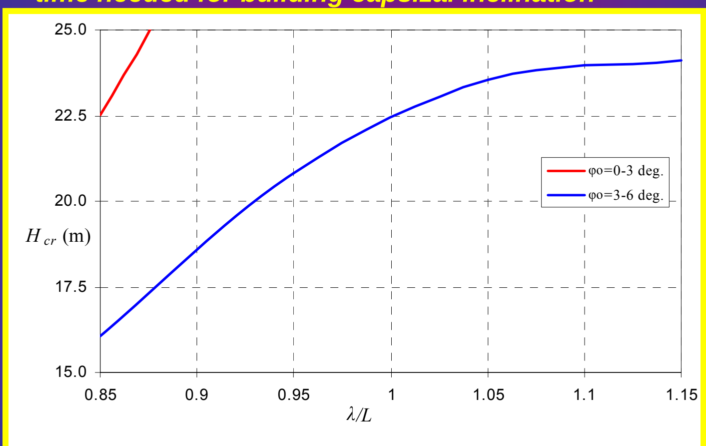
CRITICAL WAVE GROUPS (3): PURE-LOSS-OF-STABILITY (FOLLOWING SEAS)

Key condition:

time with negative restoring in the vicinity of crest

greater than

time needed for building capsizal inclination



CALCULATION OF PROBABILITIES

Mean seasonal (winter) values of wave parameters considered.

JONSWAP spectrum assumed for sea waves.

Encounter wave spectrum taken into account.

Probabilities expressed as percentage of critical time t_i scaled with respect to the time of exposure:

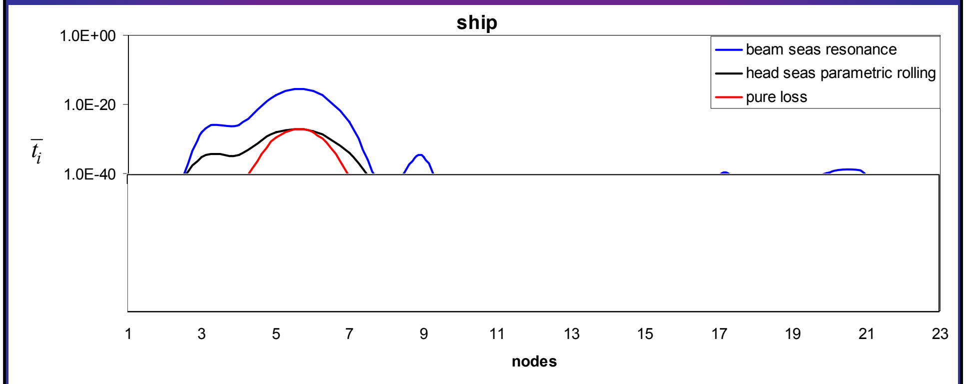
$$\overline{t_i} = \frac{t_i}{t_{tot}} = P_i \frac{T_i}{T_m}$$

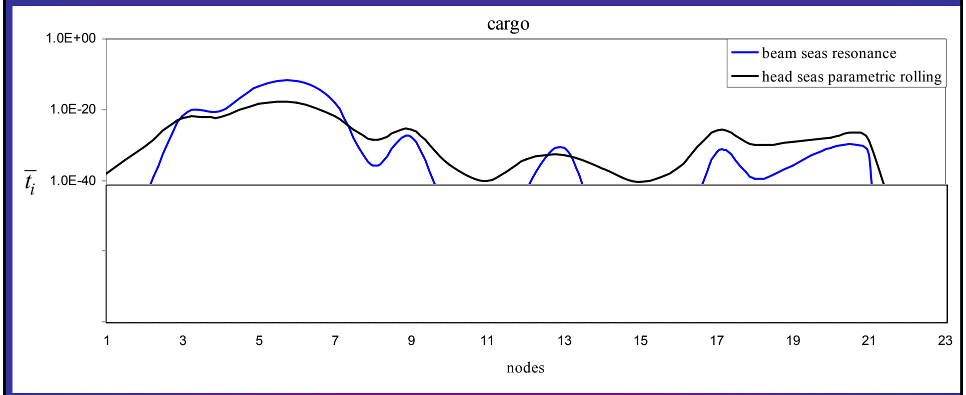
P_i = probability of a wave group i having wave period around T_i.

t_{tot} = duration of the part of the voyage inside the influence area of the considered node.

T_m = mean wave period associated with the weather node.

"CRITICAL TIME RATIO" ALONG ROUTE PER TYPE OF INSTABILITY



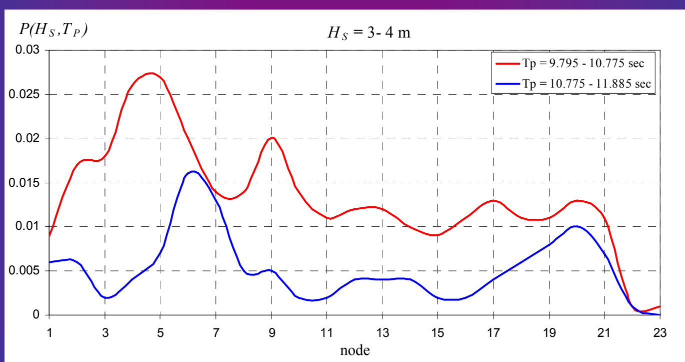


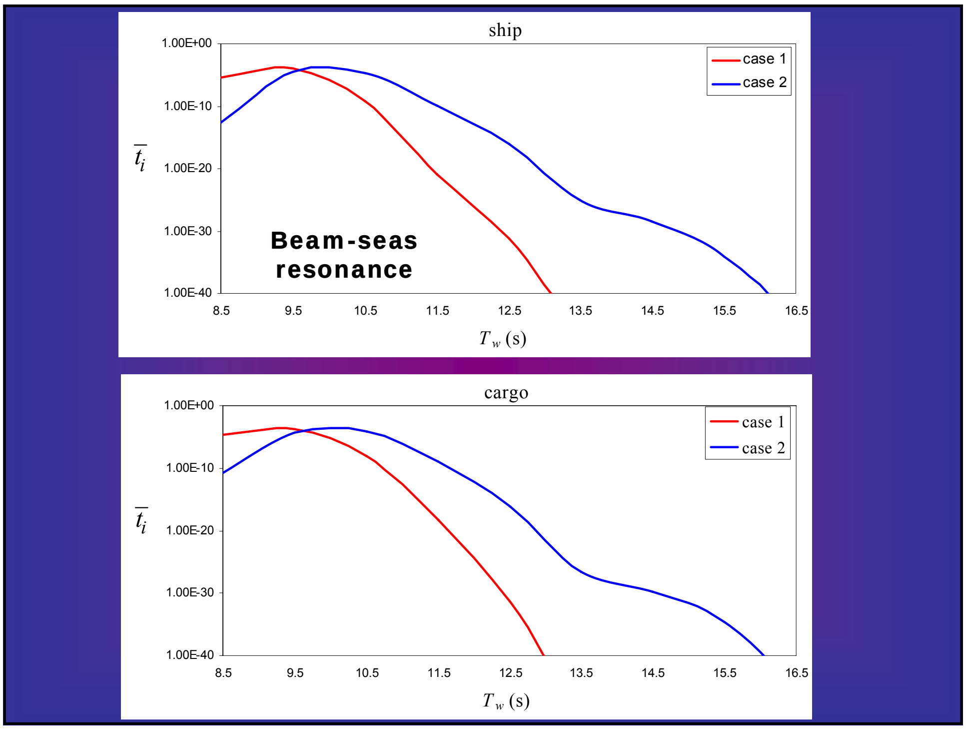
COLLECTIVE CRITICAL TIME RATIOS (ALL INSTABILITIES) FOR ENTIRE JOURNEY:

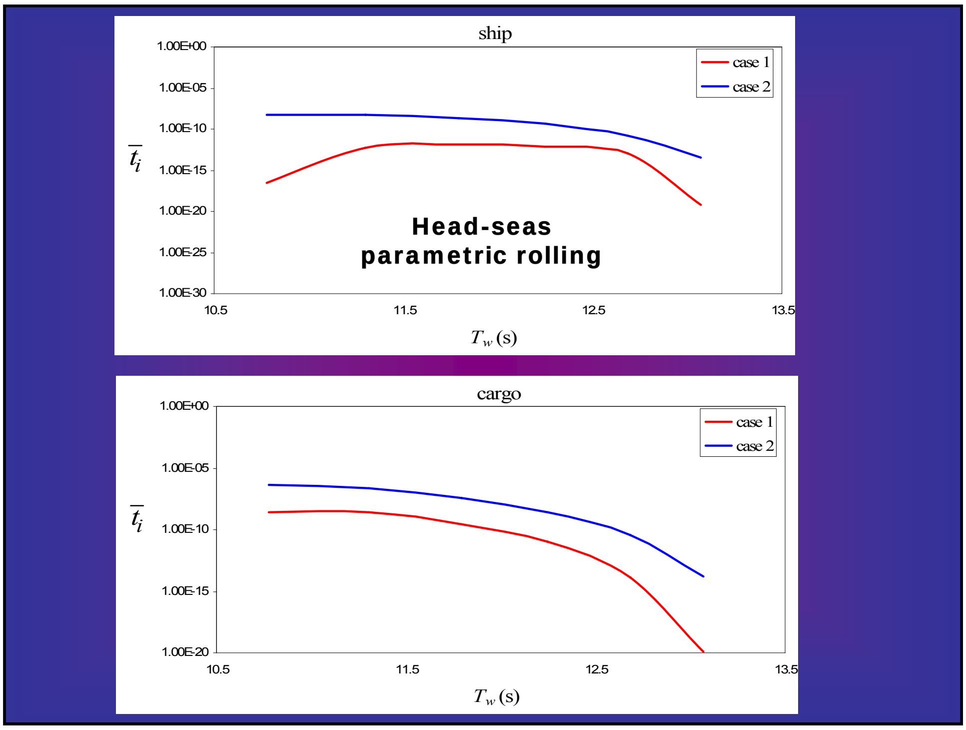
Ship (ϕ>35^0)	9.55E−17
Cargo (a_y>6.04 m/s^2)	1.14E−12

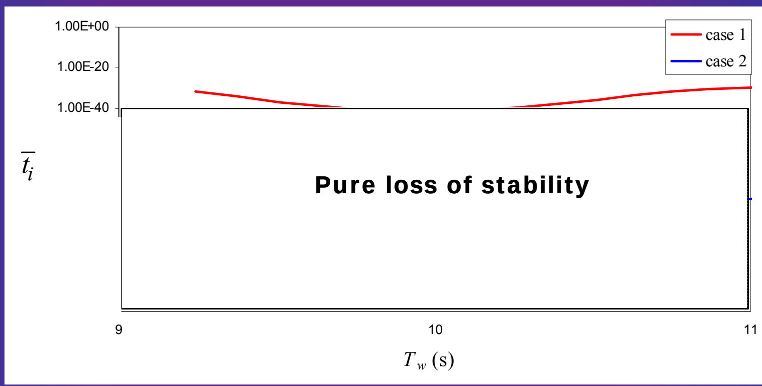
PARAMETRIC STUDY FOR EXTREME WEATHER

Case	H_S (m)	Mean H_S (m)	T_P (s)	Mean T_P (s)
1	3-4	3.5	9.795 – 10.775	10.285
2	3-4	3.5	10.775 – 11.885	11.330




ship
1.00E+00
1.00E-10
1.00E-20
1.00E-30
1.00E-40
case 1
case 2
Beam-seas
resonance
8.5
9.5
10.5
11.5
12.5
13.5
14.5
15.5
16.5
T_w (s)
cargo
1.00E+00
1.00E-10
1.00E-20
1.00E-30
1.00E-40
case 1
case 2
8.5
9.5
10.5
11.5
12.5
13.5
14.5
15.5
16.5
T_w (s)


ship
1.00E+00
1.00E-05
1.00E-10
1.00E-15
1.00E-20
1.00E-25
1.00E-30
case 1
case 2
Head-seas
parametric rolling
10.5
11.5
12.5
13.5
T_w (s)
cargo
1.00E+00
1.00E-05
1.00E-10
1.00E-15
1.00E-20
case 1
case 2
10.5
11.5
12.5
13.5
T_w (s)



Critical time ratios (overall) for extreme weather

	Case 1	Case 2
Ship ($\phi > 35^0$)	3.55E-5	2.12E-5
Cargo ($a_y > 6.04$ m/s^2)	7.60E-5	4.08E-5

CONCLUDING REMARKS

•A practical probabilistic stability assessment method that is embeddable upon a “risk-based” framework of assessment has been developed during the SAFEDOR project.

•It was succeeded to exploit the strength of deterministic approach and to provide a bridge with state-of-the-art wave/wind models.

•The feasibility of the method was shown through application to a Ropax ferry that was assessed for operation on a specific route across the Mediterranean Sea. A further study for a containership is nearing completion.