International Association of Oil & Gas Producers

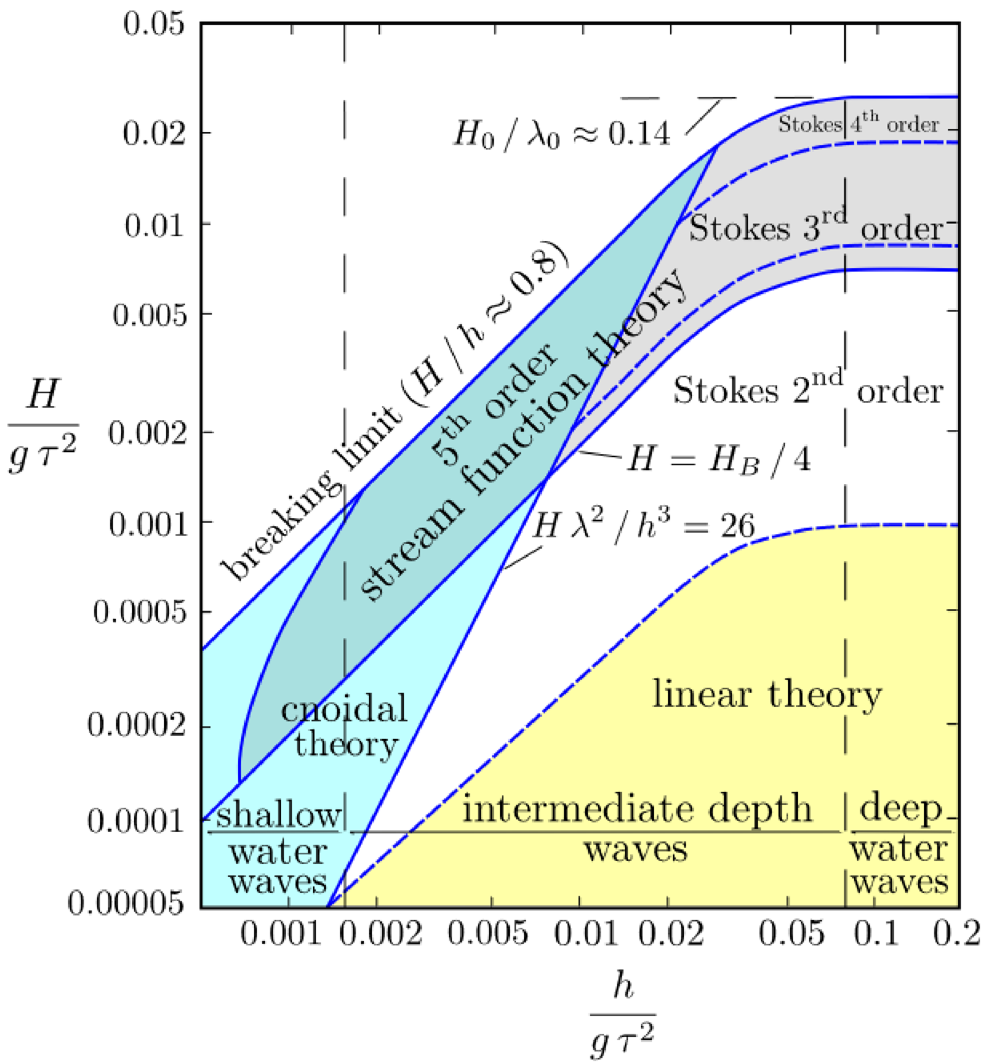
virtual engagement session for OSRC 2021
fixed offshore structures

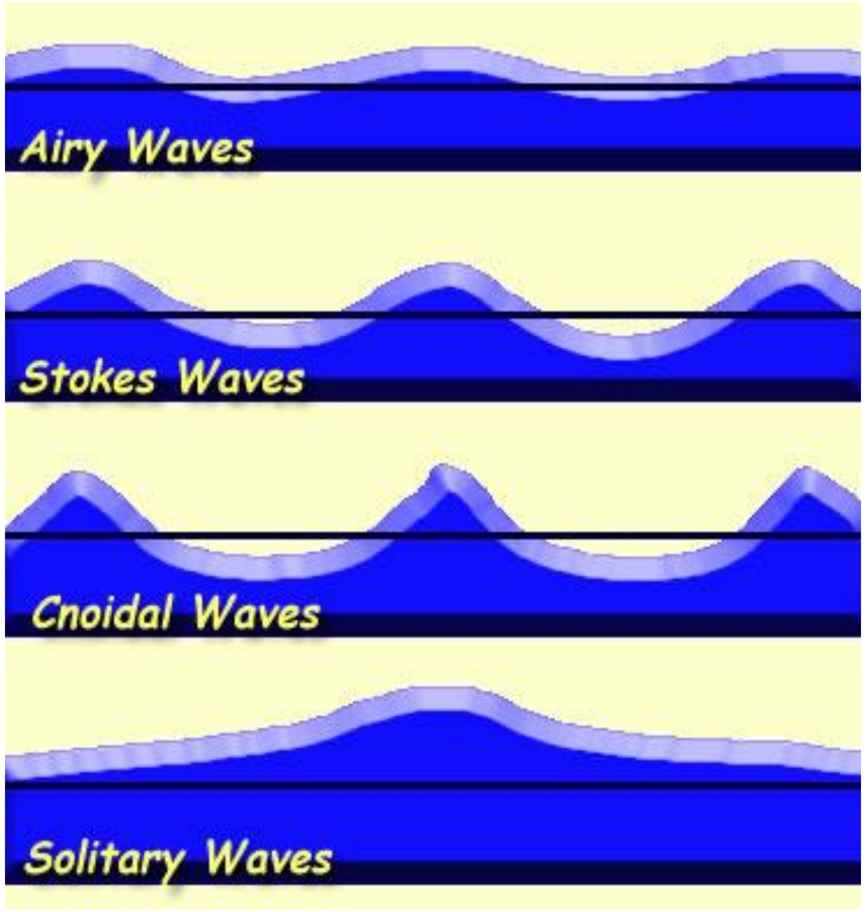
pre-meeting video 3
metocean probability & statistics

pre-meeting background on…

- basic probability and statistics
- structural probability and statistics
- metocean probability and statistics

regular (periodic) wave theory – applicability limits

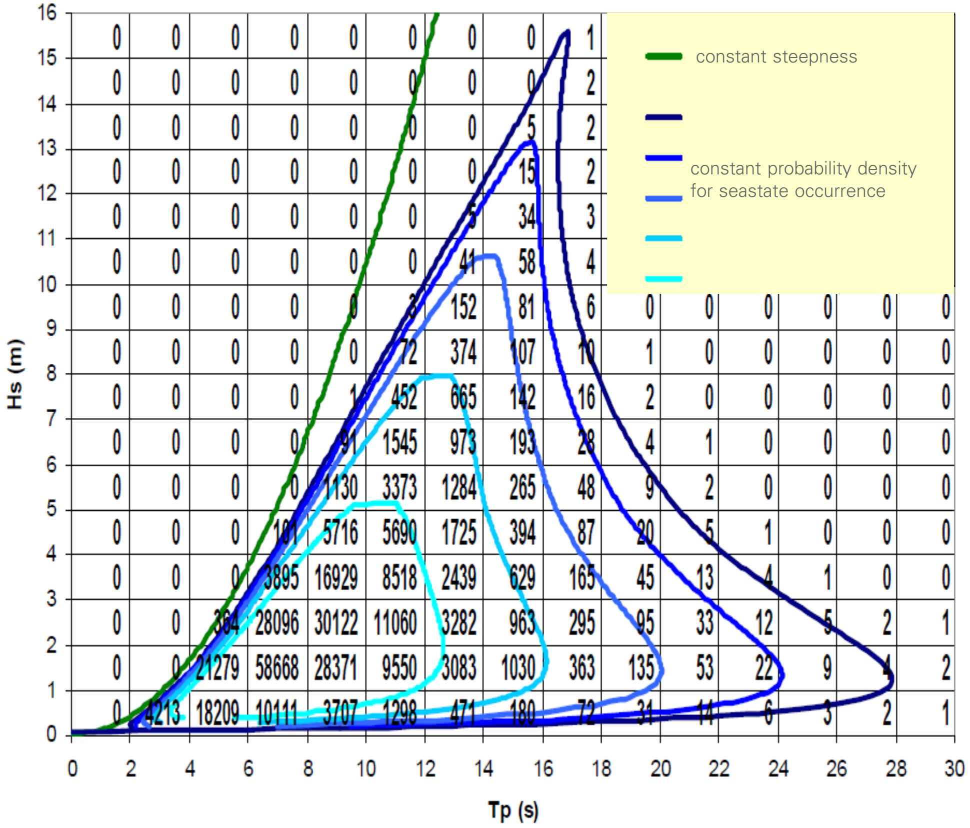


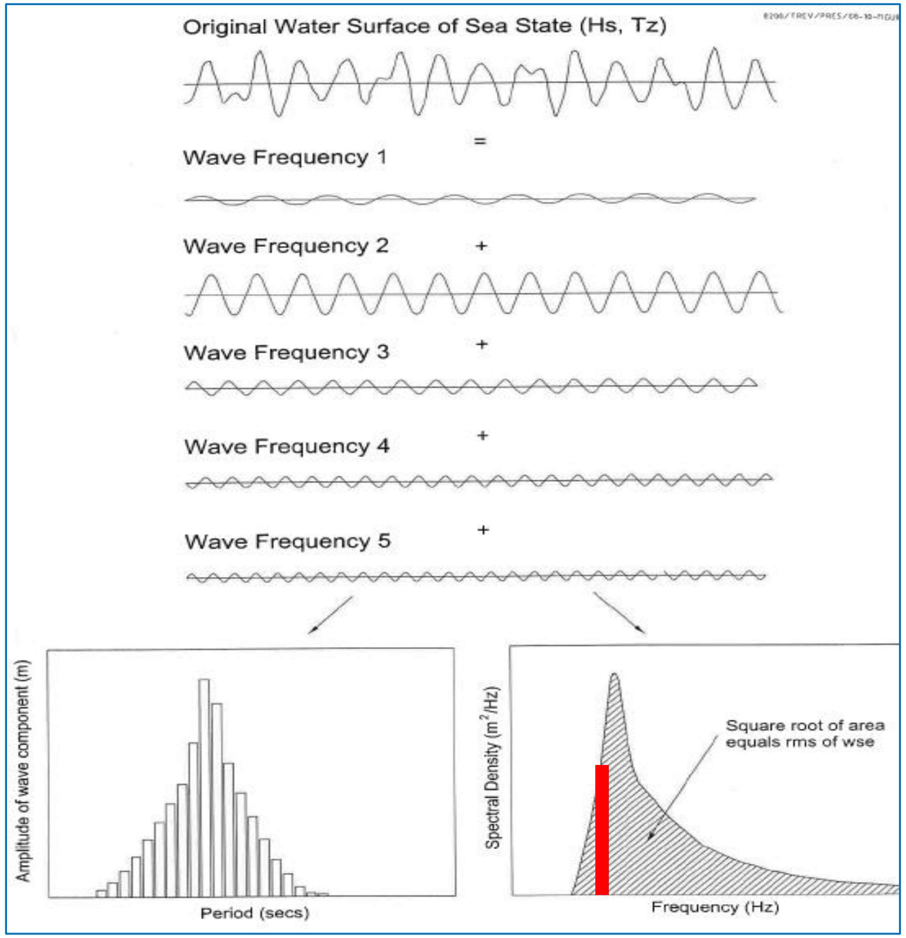


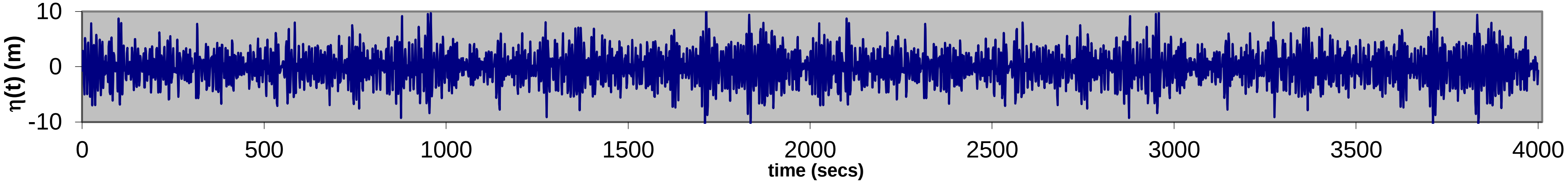
random irregular wave theory (real waves)

International Association of Oil & Gas Producers

Sea states, spectra and wavelets

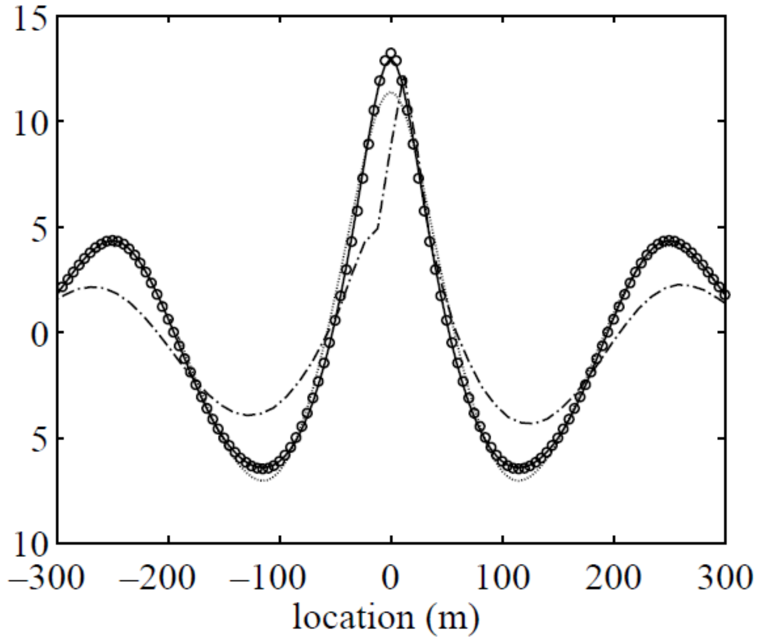


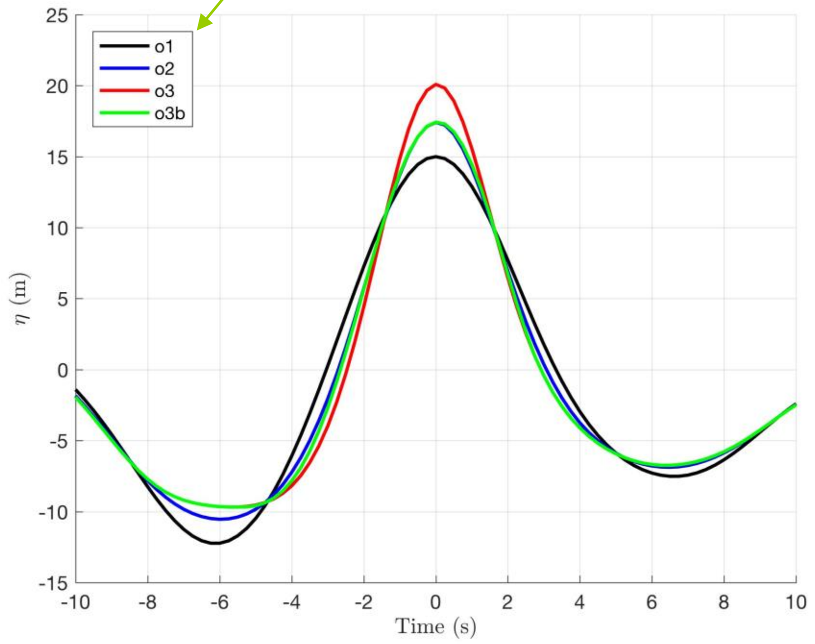




deterministic irregular wave theory
(NEWWAVE or focused wave)

1st, 2nd, 3rd order & breaking

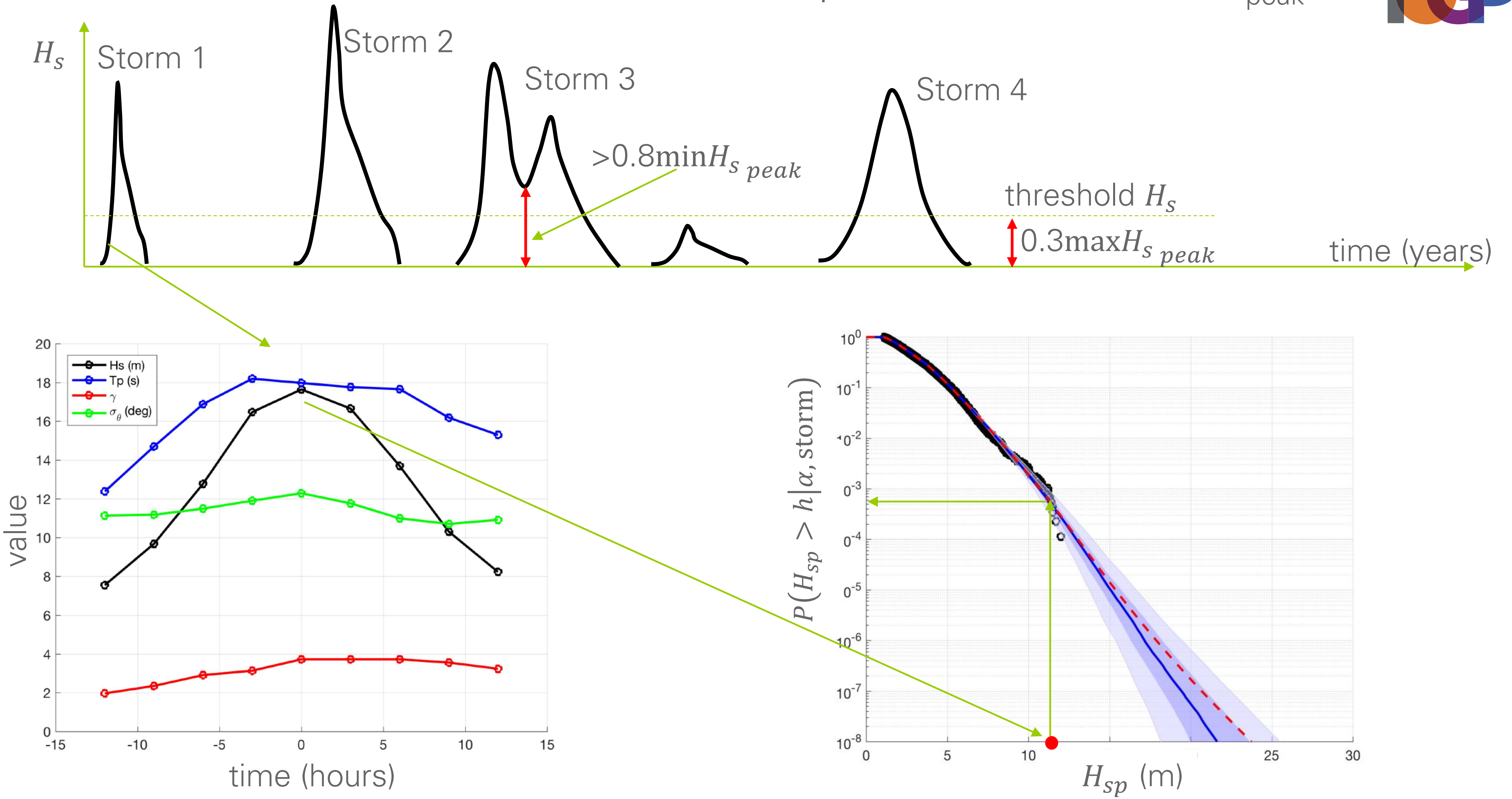




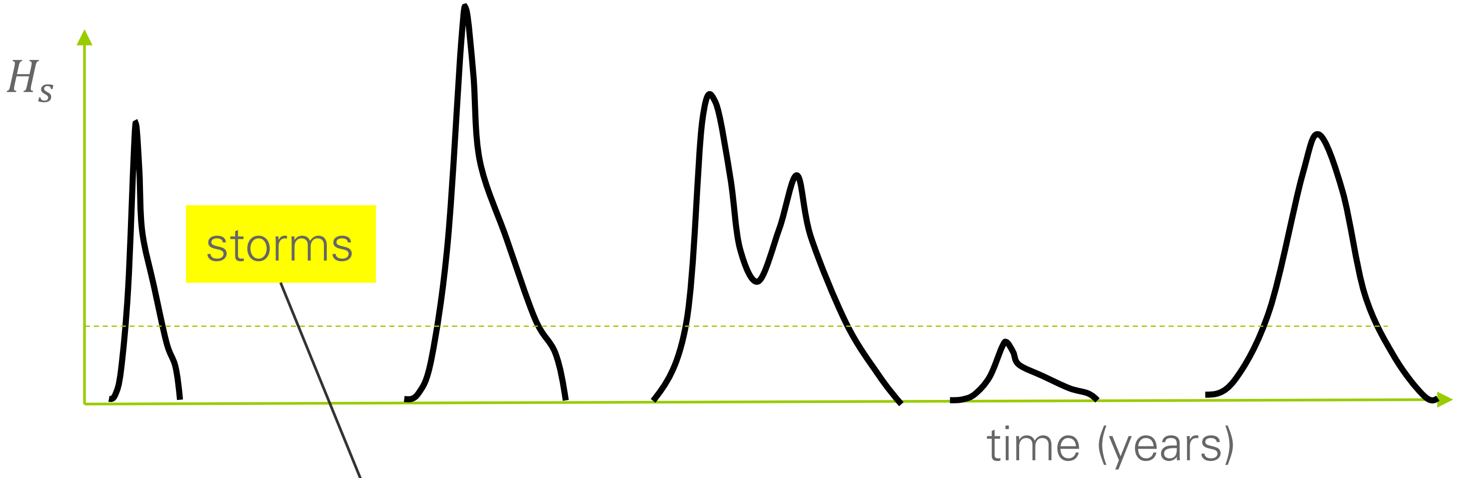
Focused (NewWave) inc higher order theory
Dotted=linear; solid=2nd order; open circle=3rd order; dash-dotted=fully nonlinear.

Unfocused wave

metocean environment - storms, profiles, sea states, Hs_{peak}



metocean environment - storms, profiles, sea states, waves

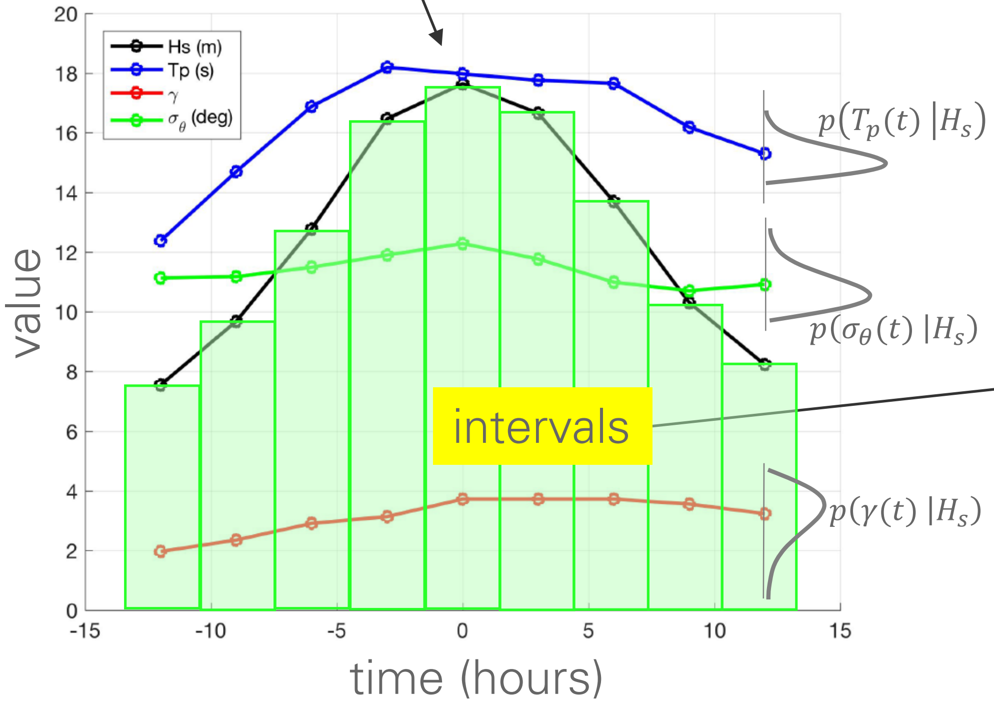


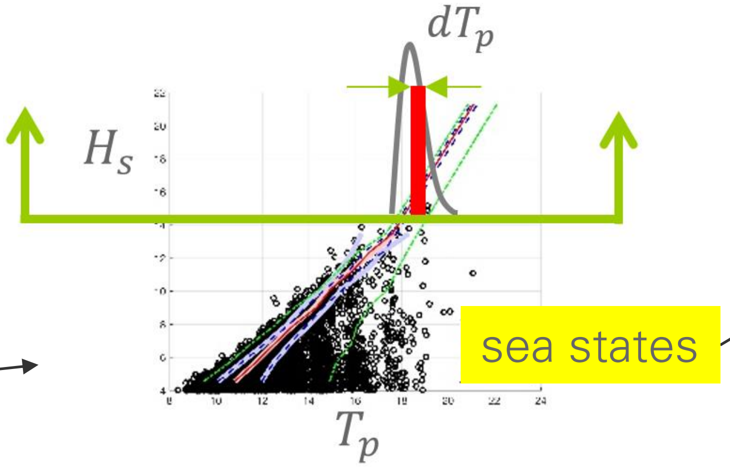
Taylor, Jonathan & Harland(97) - Constraining a Random Process

The local shape of large ocean waves is very variable. This variability in the shape of a wave, and the random motion of the structure in response to waves prior to the large wave, produces considerable variability in the peak structural response associated with a large wave of given elevation.

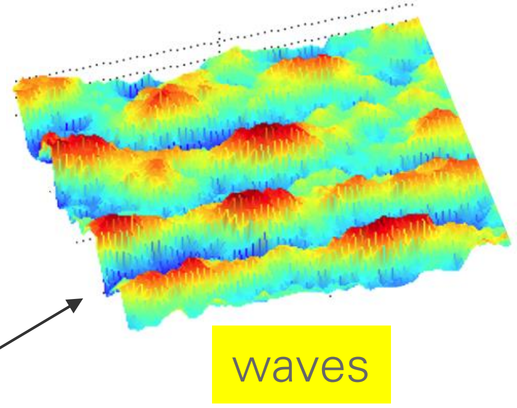
For the largest waves in the sea-state, this shape tends to a NewWave (Tromans et al., 1991, Jonathan, Taylor and Tromans, 1994).

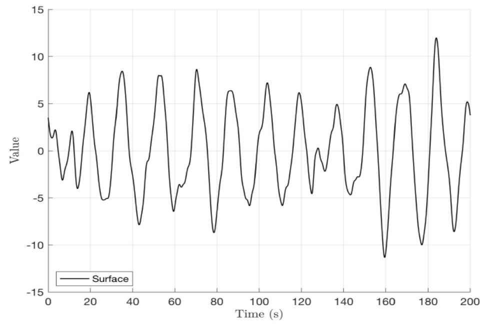
We constrain a random time series for surface elevation to have a large crest of a given size at a chosen time in such a way that, in statistical terms, the extreme is effectively indistinguishable from a purely random occurrence of a crest of that height. (100x3hrs simulations to 1x120sec)



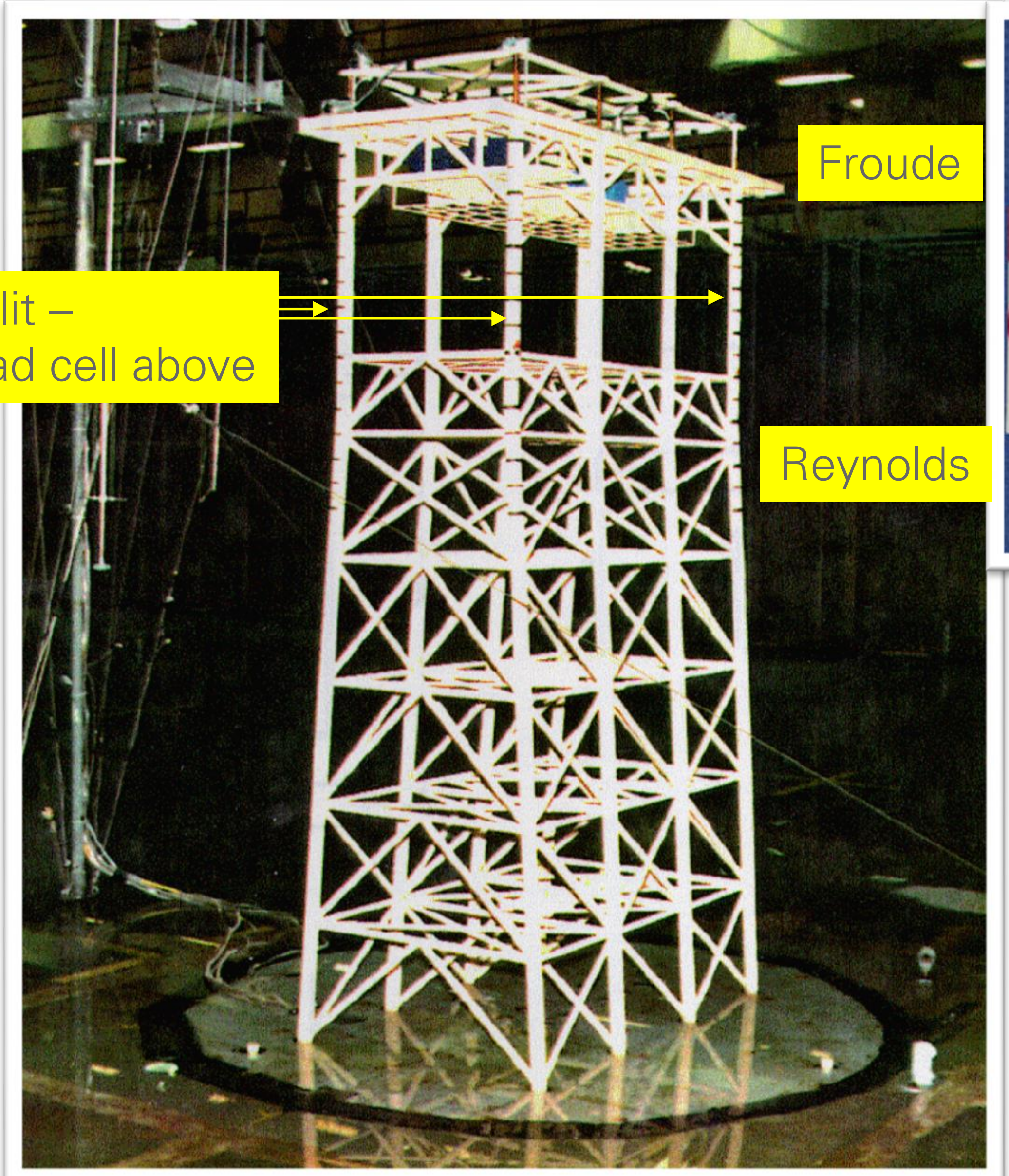


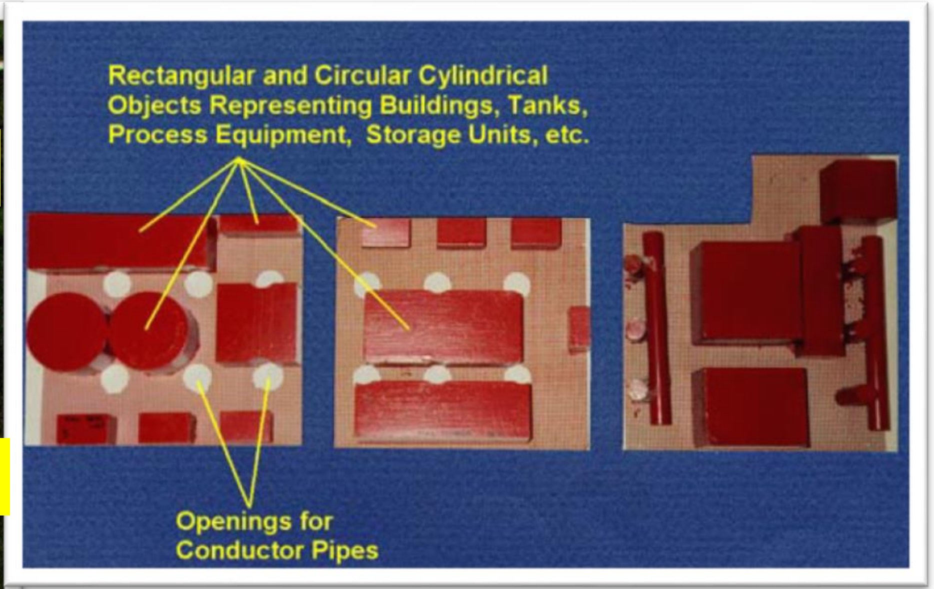
$$p(T_p, \sigma_\theta, \gamma, \eta_{swl}, u, \theta_u, w, \theta_w \ldots |H_s)$$



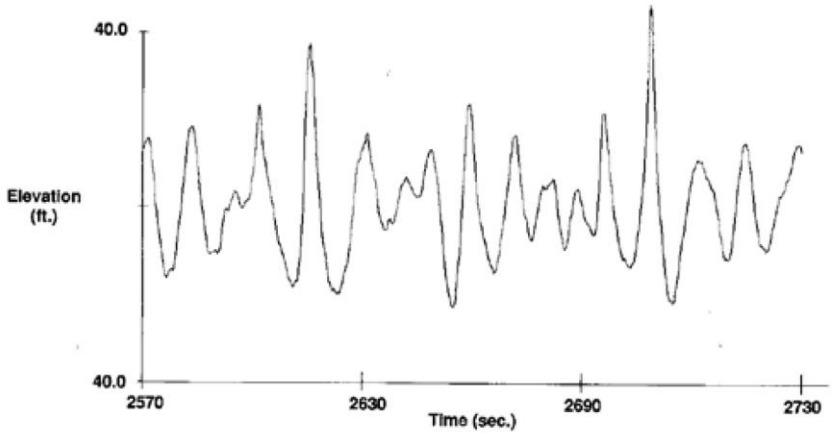


1988-89 WiD experiments - Finnigan and Petrauskas





deck type
- heavily equipped (solid)
- moderately equipped
- bare (no equip)



irregular wave

1988-89 WiD experiments - Finnigan and Petrauskas

International Association of Oil & Gas Producers

Silhouette method for horizontal wave-in-deck force

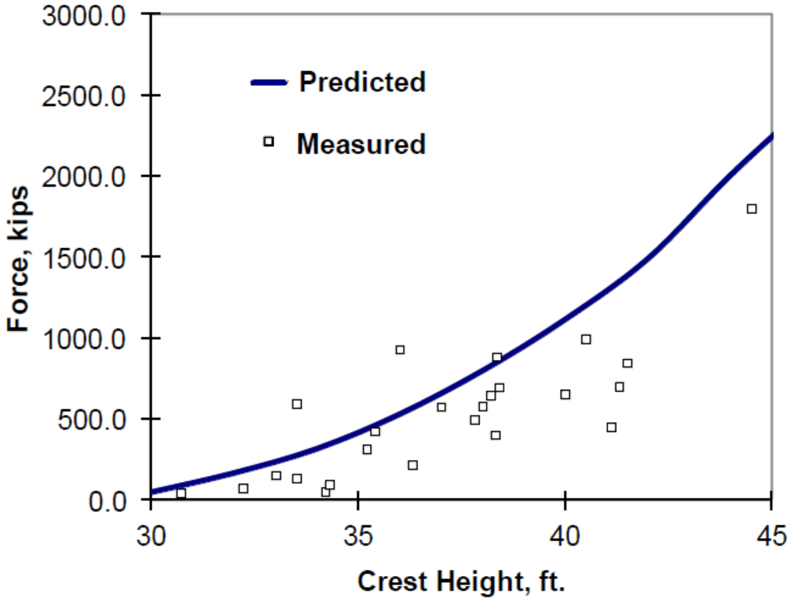


Figure 15. Comparison Of Measured And Predicted (API Guidelines) Moderate Deck Forces, 90 Degree Heading

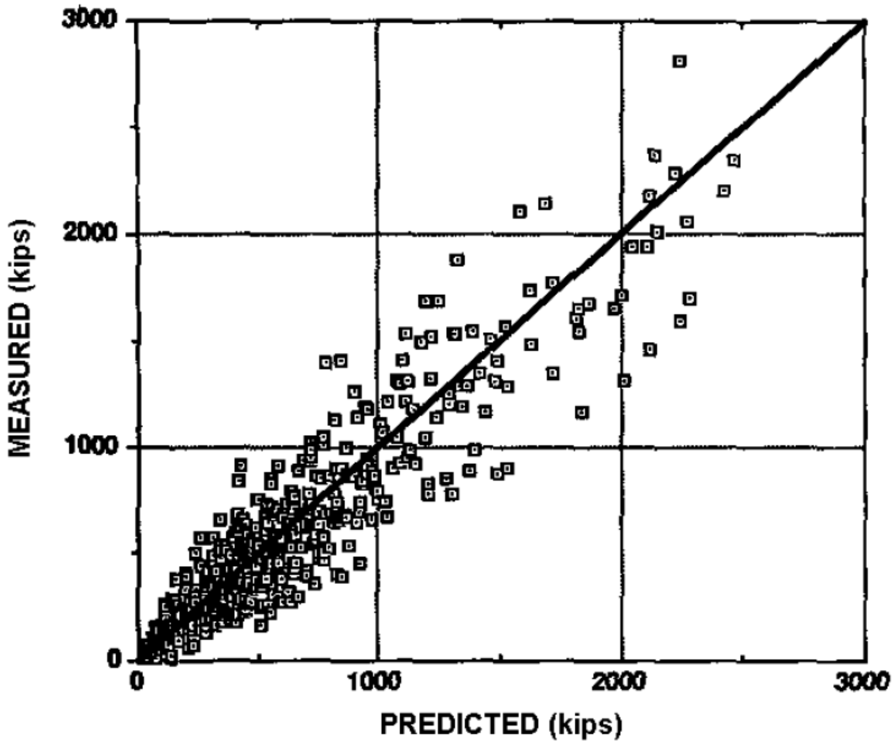


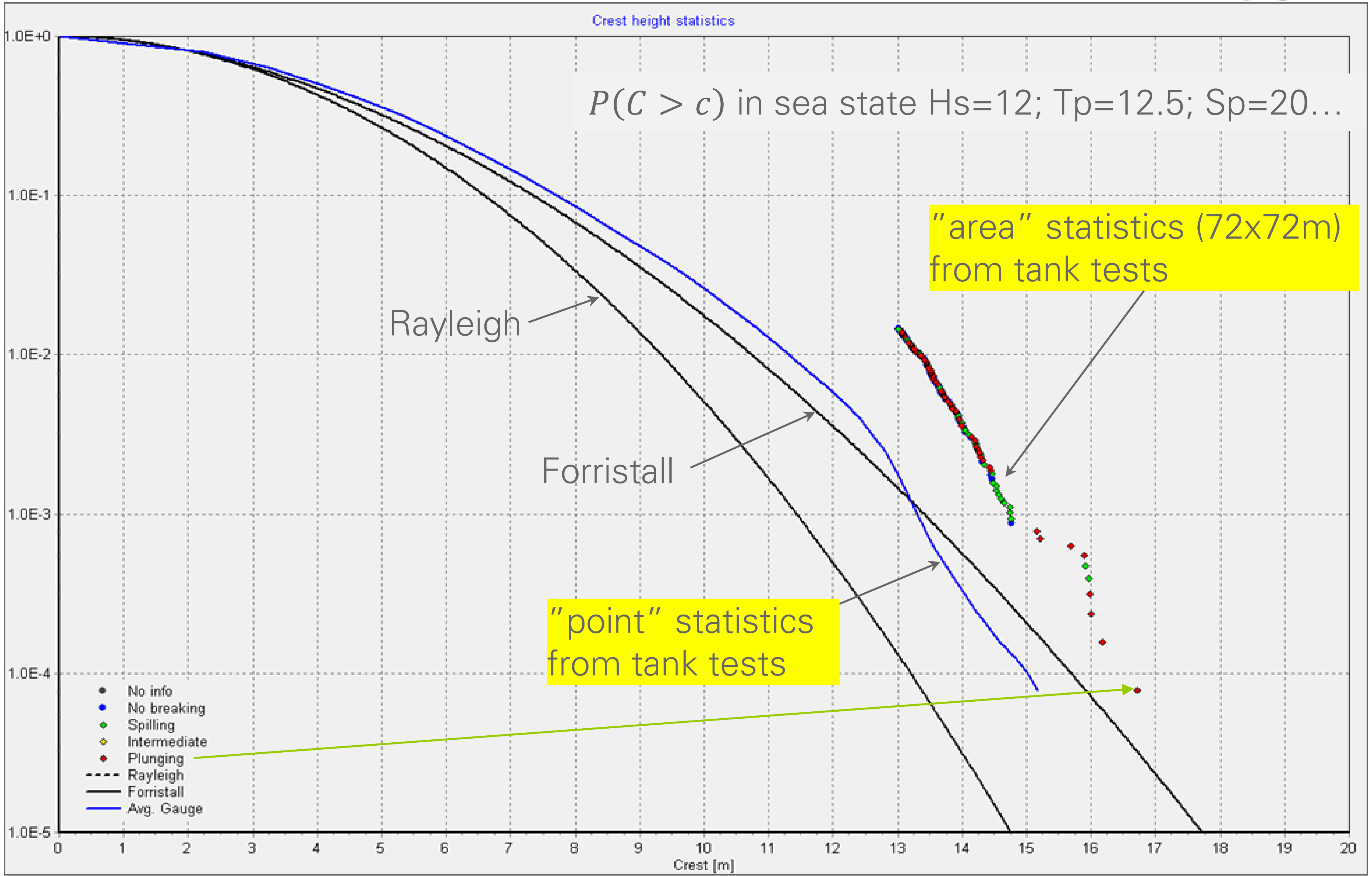
Figure 13. Measured Vs. Predicted Deck Force Data Based On Measured Crest Height, (all 2D & 3D tests, 532 impacts).

Finnigan and Petrauskas – removed all test results from breaking waves

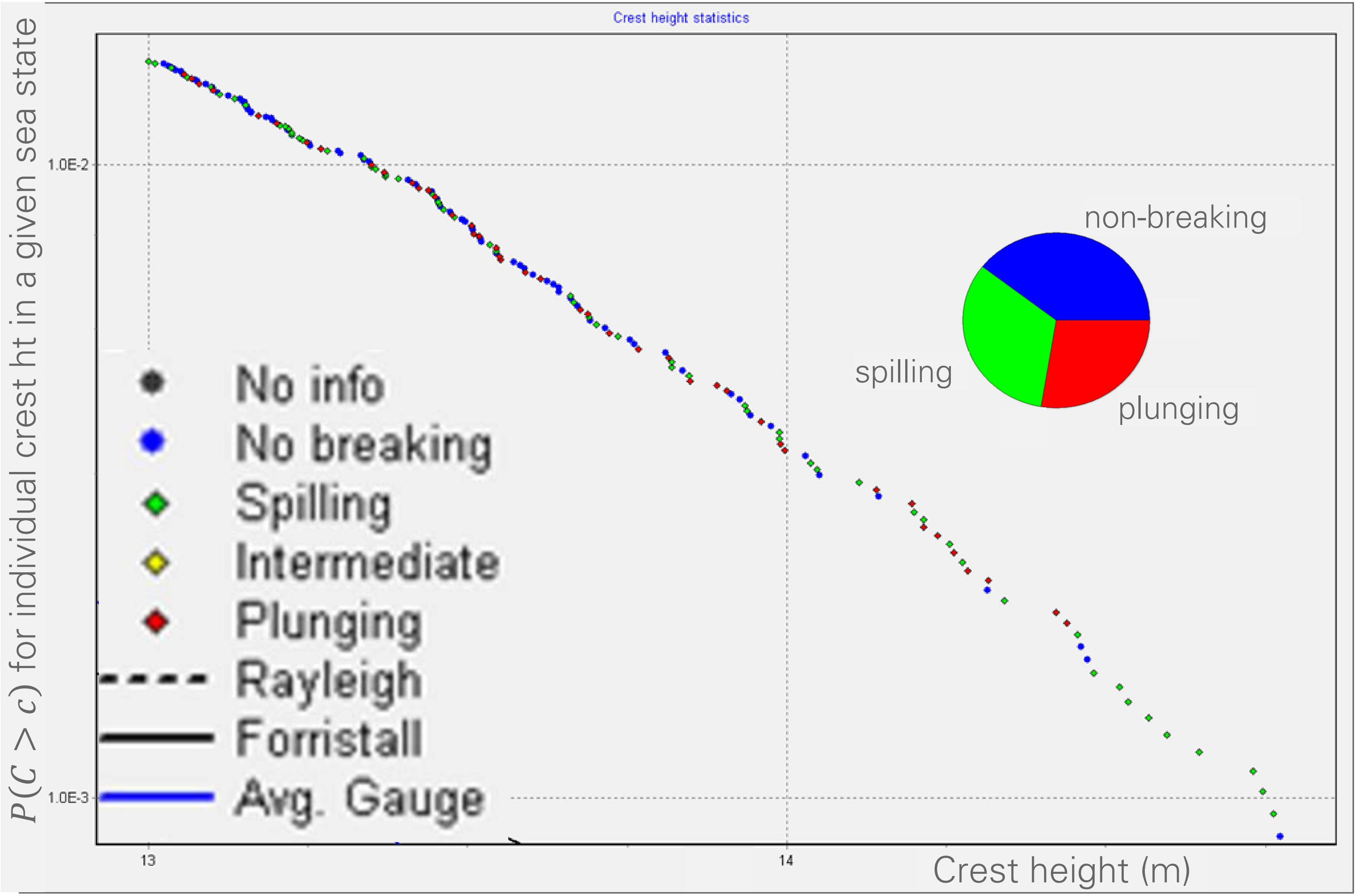
crest height exceedance (latest knowledge)

$P(C > c)$

probability of exceedance of individual crest ht (C) in a given sea state



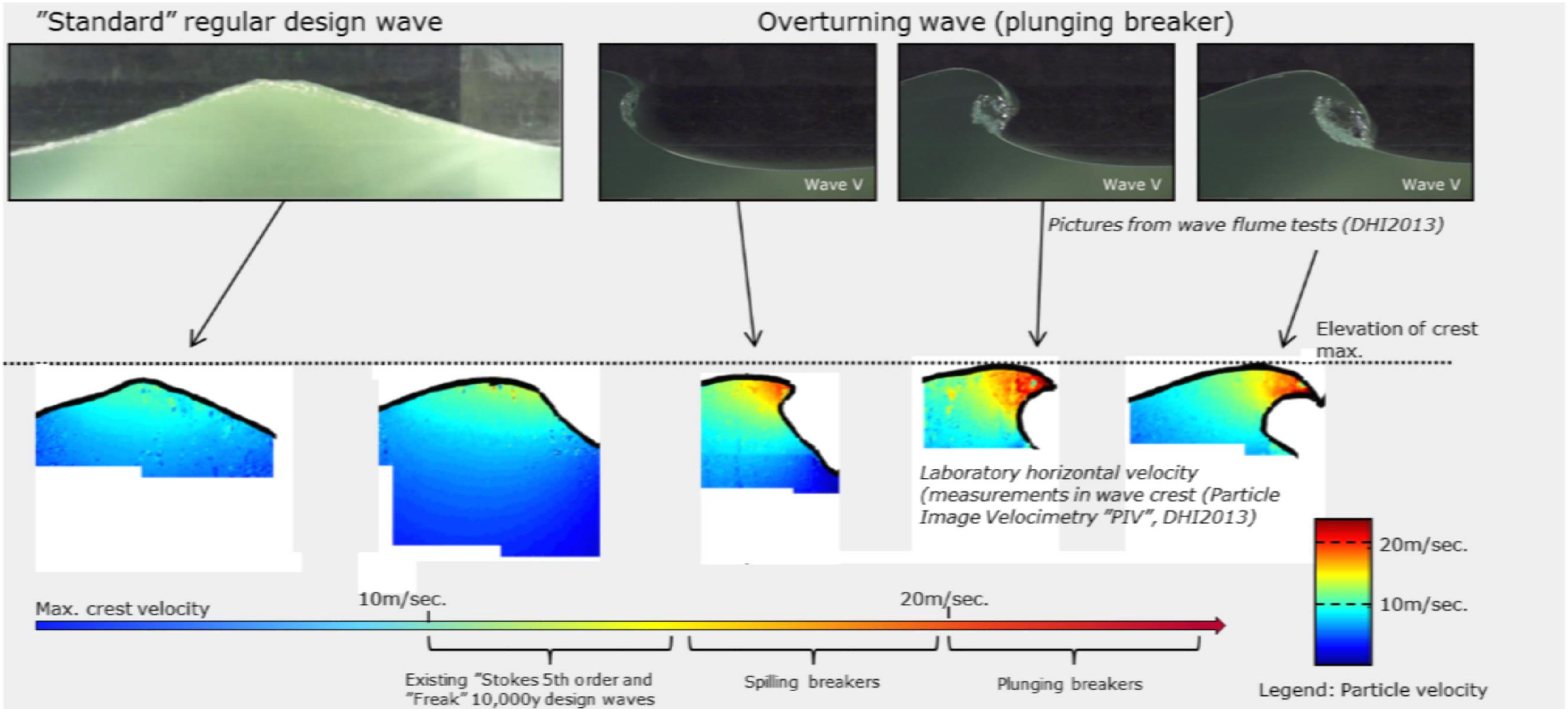
crest height exceedance (latest knowledge)



last plot – zoomed in at around 14m crest

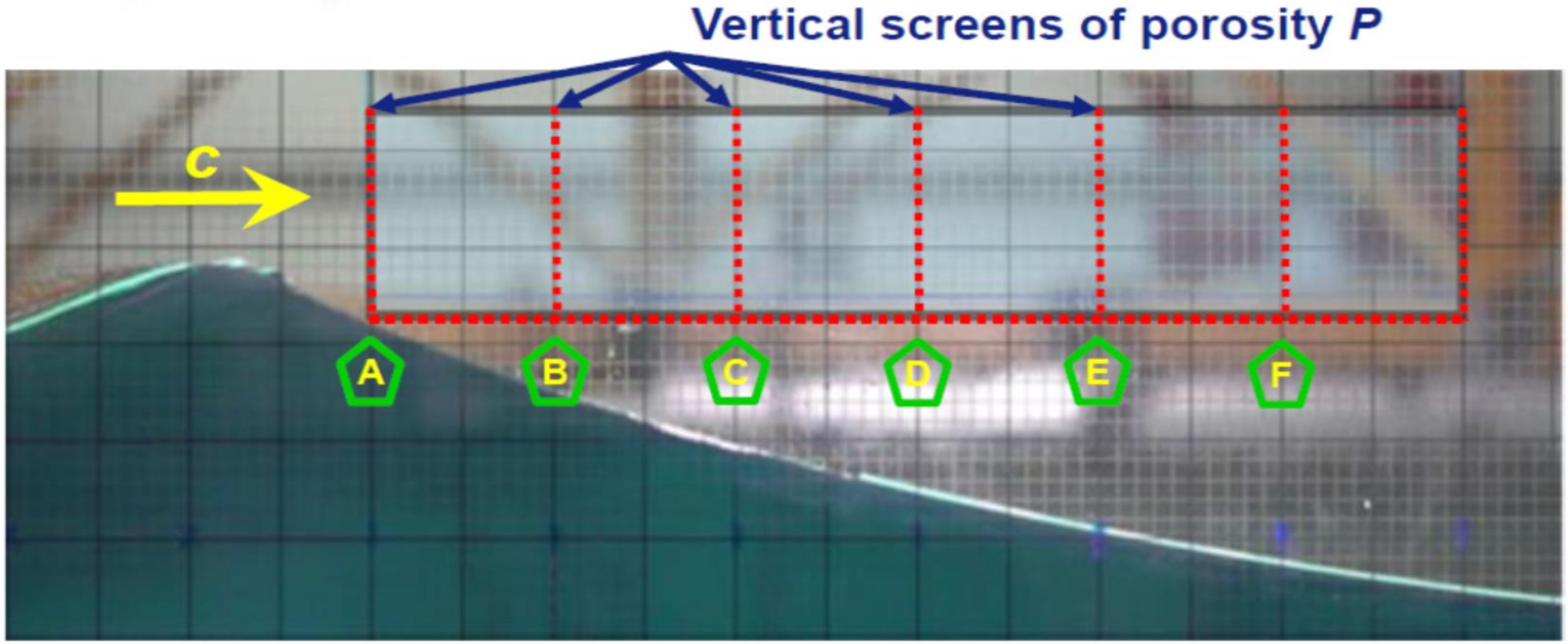
note types of breaking

crest velocity with breaking



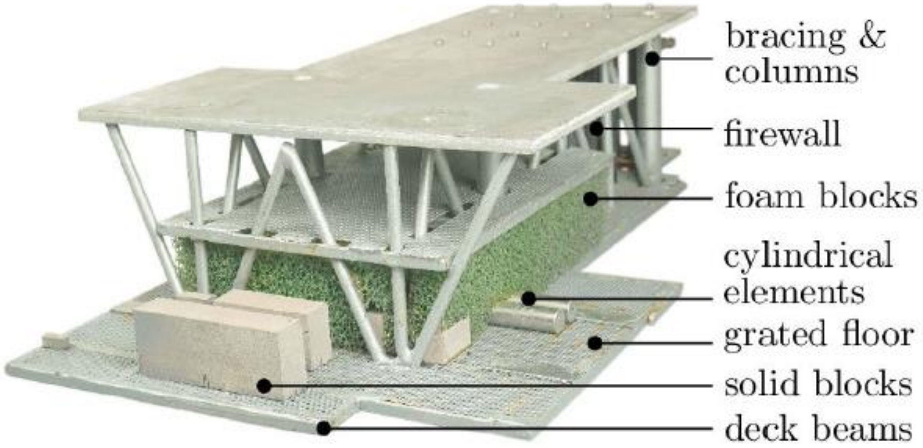
wave-in-deck load – momentum flux

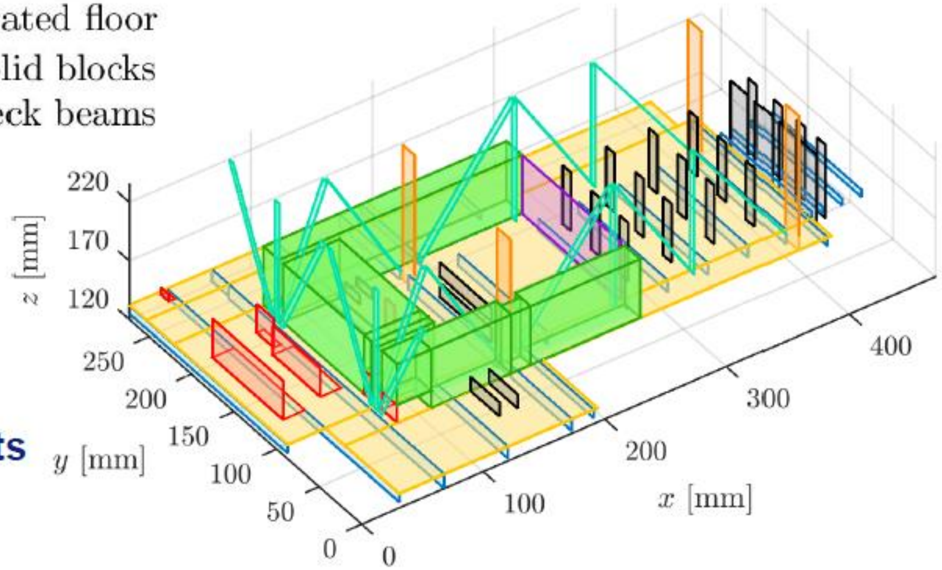
- Differs from original implementation of Graff et al (1995)
- Accounts for the porosity, *P*, of the deck structure
- Lagrangian formulation - following a ‘patch’ of fluid
- Allows fluid to enter the deck (depending on *P*).
- Describes the progressive destruction of momentum
- Includes the possibility of some momentum escaping
- Based on knowledge of the incident wave, $\eta(x,y,t)$ and $\overline{u}(x,y,z,t)$
- No empirical input



wave-in-deck load – measured from model test

- **Application to Maersk's Tyra West Charlie (TWC)**
  - **Small steel jacket structure**
  - **Water depth: *d*=45m**
  - **Low deck elevation (sea bed subsidence)**





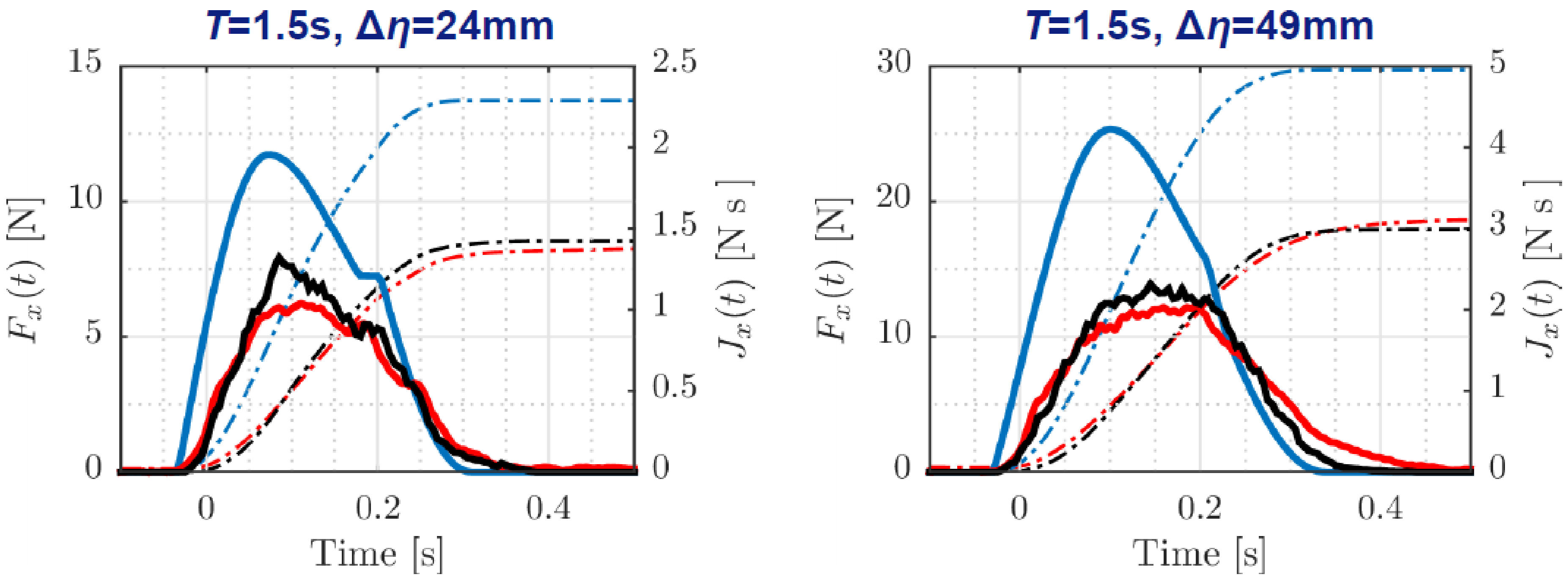
Discretised topside incorporating:
- (a)-(d)
- Large deterministic wave events
- Varying levels of inundation

Model topside structure incorporating:
a) Main structural members
b) Blast wall
c) Grated deck
d) Large plant

wave-in-deck load – measured from model test

IOGP International Association of Oil & Gas Producers

Total horizontal force (LH axis) & total horizontal impulse (RH axis)

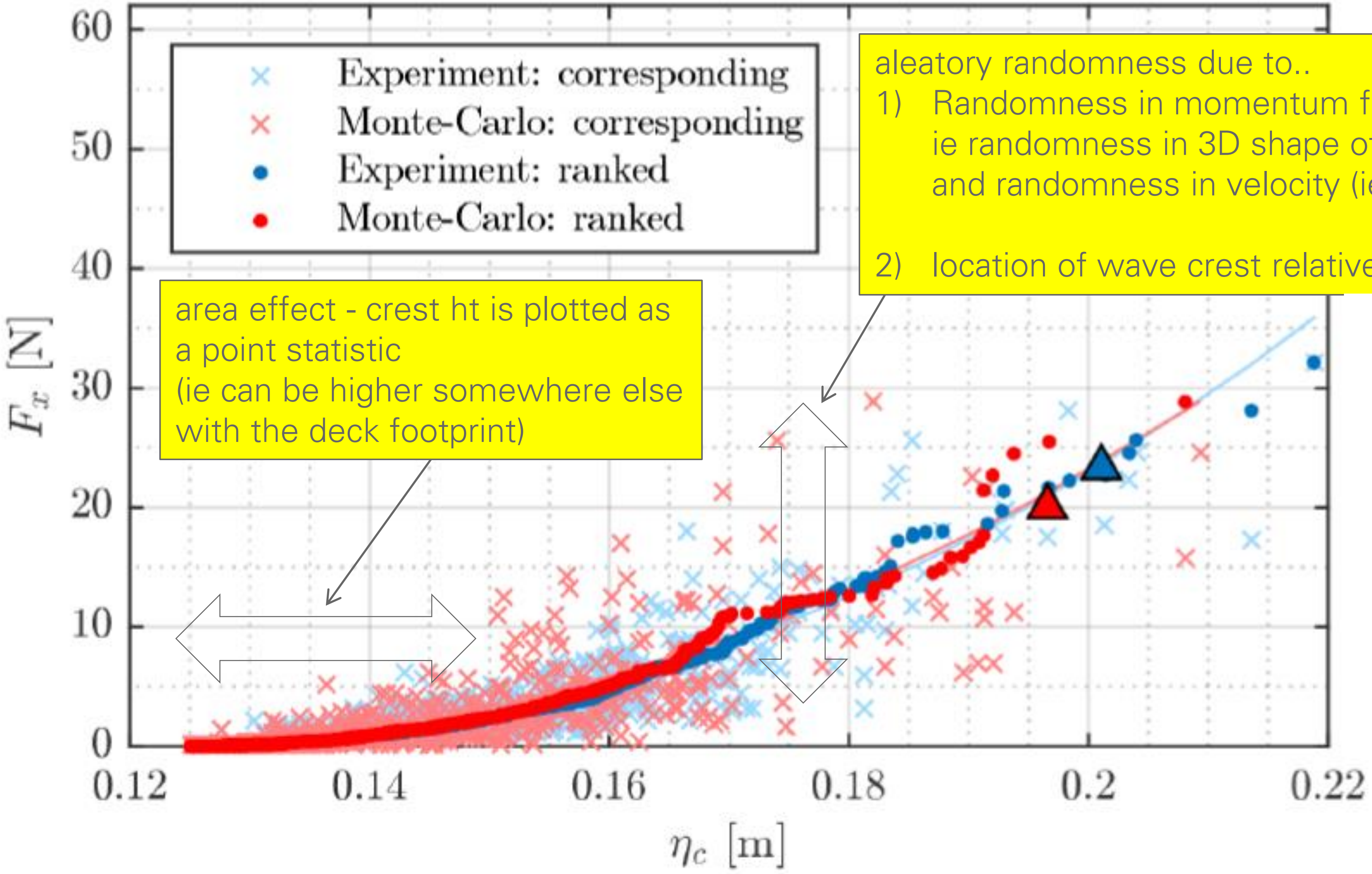


Red lines: measured data (load cells) **Blue line: Graff et al (1995)** **Black line: present model**

Note – units are for model scale!

wave-in-deck load – measured from model test

International Association of Oil & Gas Producers



aleatory randomness due to..

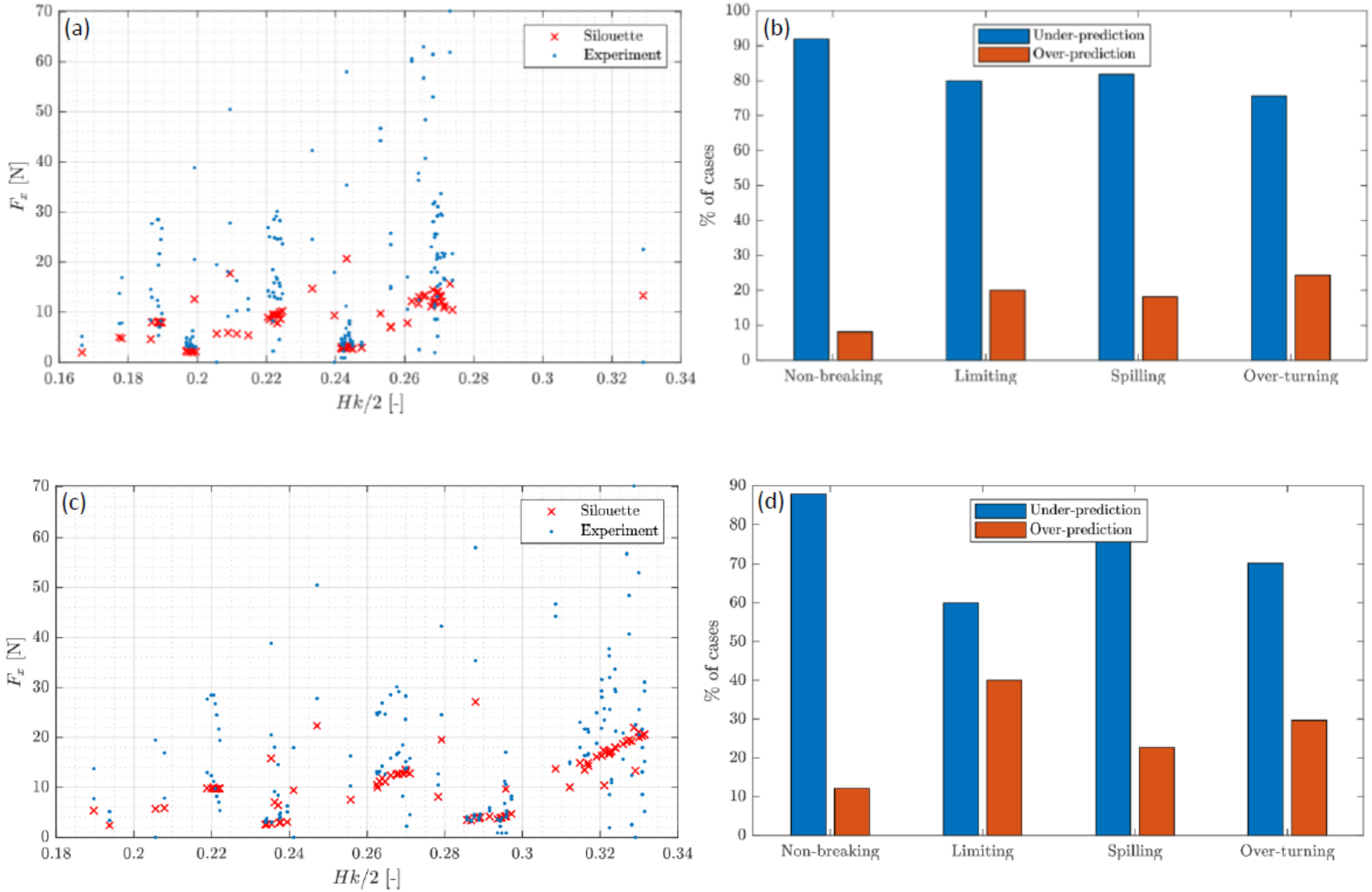
1) Randomness in momentum for a given crest ht.
   ie randomness in 3D shape of wave crest (ie mass) and randomness in velocity (ie spilling or plunging)

2) location of wave crest relative to underdeck PGs

area effect - crest ht is plotted as a point statistic
(ie can be higher somewhere else with the deck footprint)

silhouette methods (API/ ISO and Santala 2017)

International Association of Oil & Gas Producers



% underestimate

% overestimate

silhouette method 1 (API, ISO) relative to tank test

% underestimate

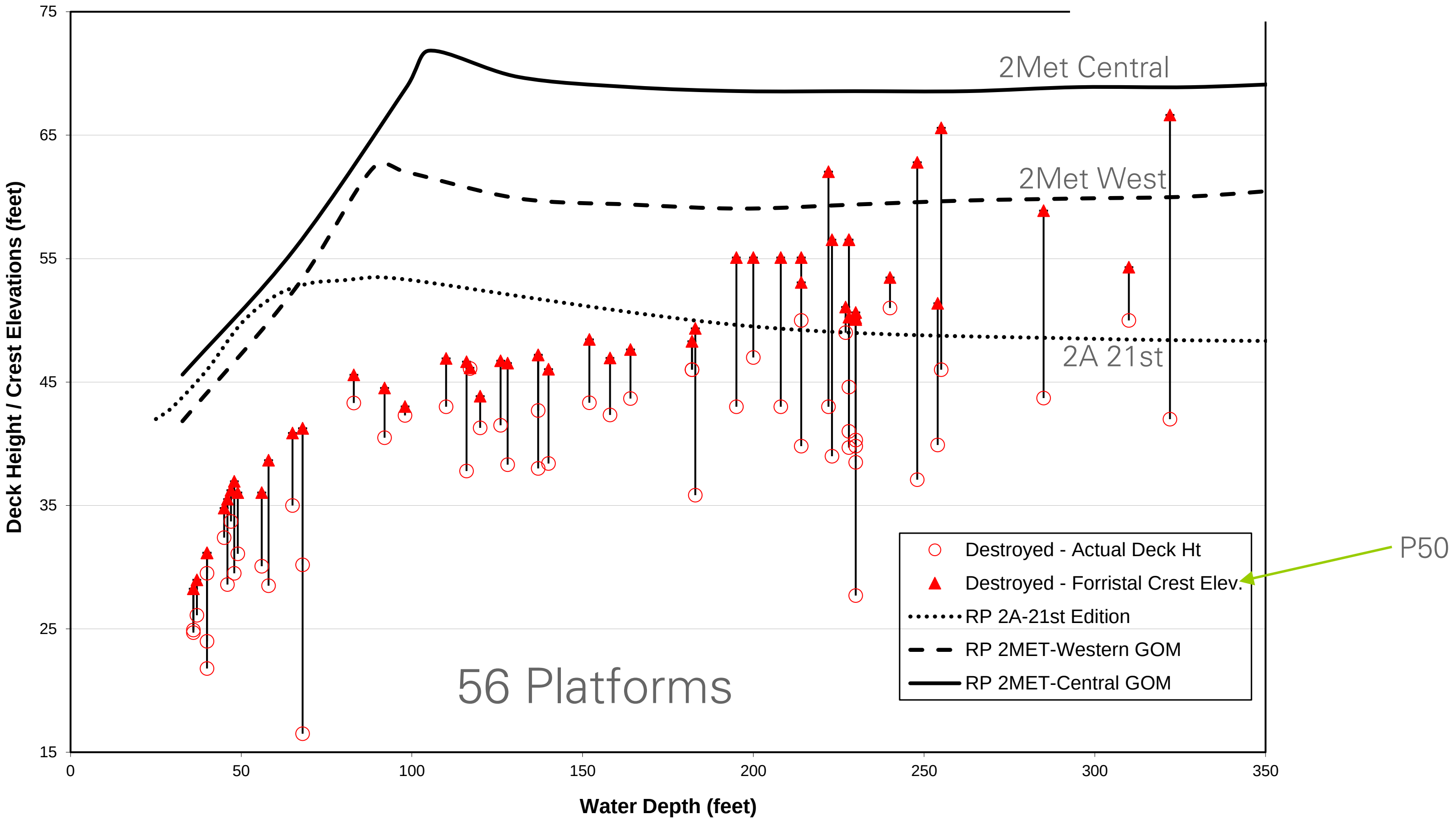
% overestimate

silhouette method 2 (Santala) relative to tank test

Figure 5.14: Comparisons between the Silhouette model (with c_d=2.5) and laboratory data based upon deterministic focused wave groups (Table 5.2) for a topside structure with P=0%; (a), (b) calculated using Method (1) and (c), (d) calculated using the updated Method (2) following Santala (2017).

P50 crest elevations – crest higher than deck

Hurricanes Katrina and Rita

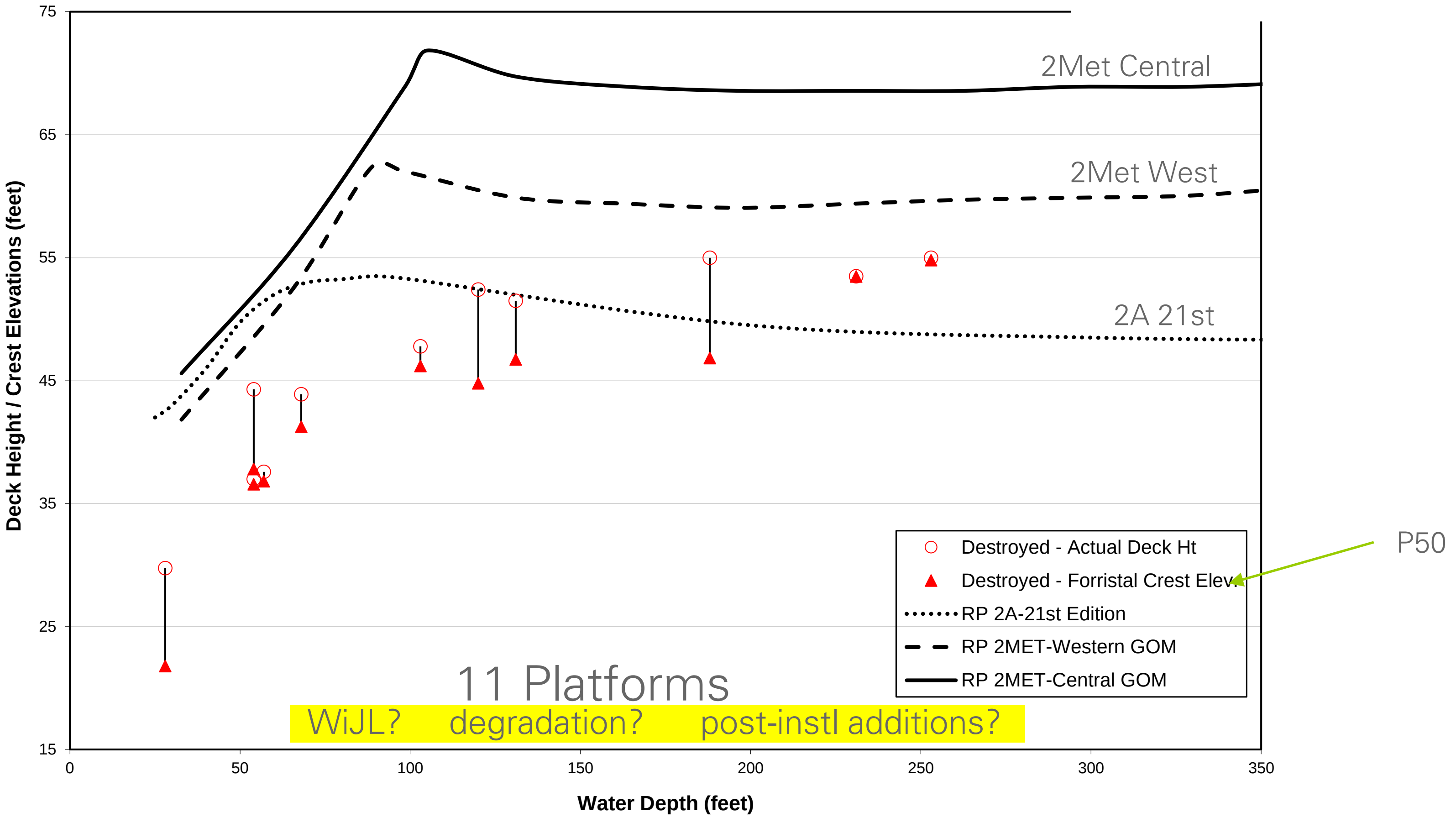


Destroyed Platforms – Platform Deck Height Compared to Predicted Wave Crest Height

P50 crest elevations – crest lower than deck

International Association of Oil & Gas Producers

Hurricanes Katrina and Rita



Destroyed Platforms – Platform Deck Height Compared to Predicted Wave Crest Height

long term P(Hs>h) for non-cyclonic storms

International Association of Oil & Gas Producers

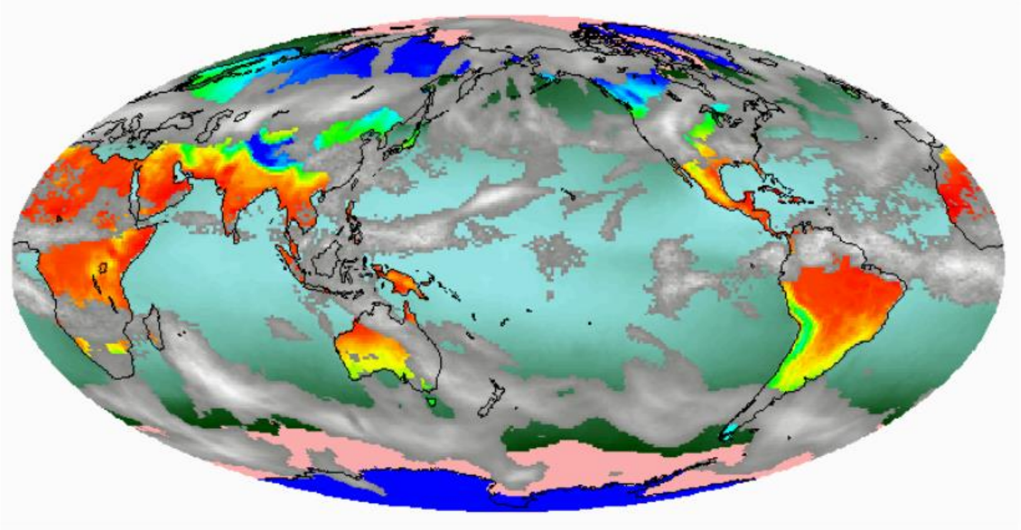
Data methods

1) Historical method
- data, either from measurements or model hindcasts
- pooled locations
- track shifting

2) Deductive method
- very rare synthetic storms

3) Simulation method
- free running climate model

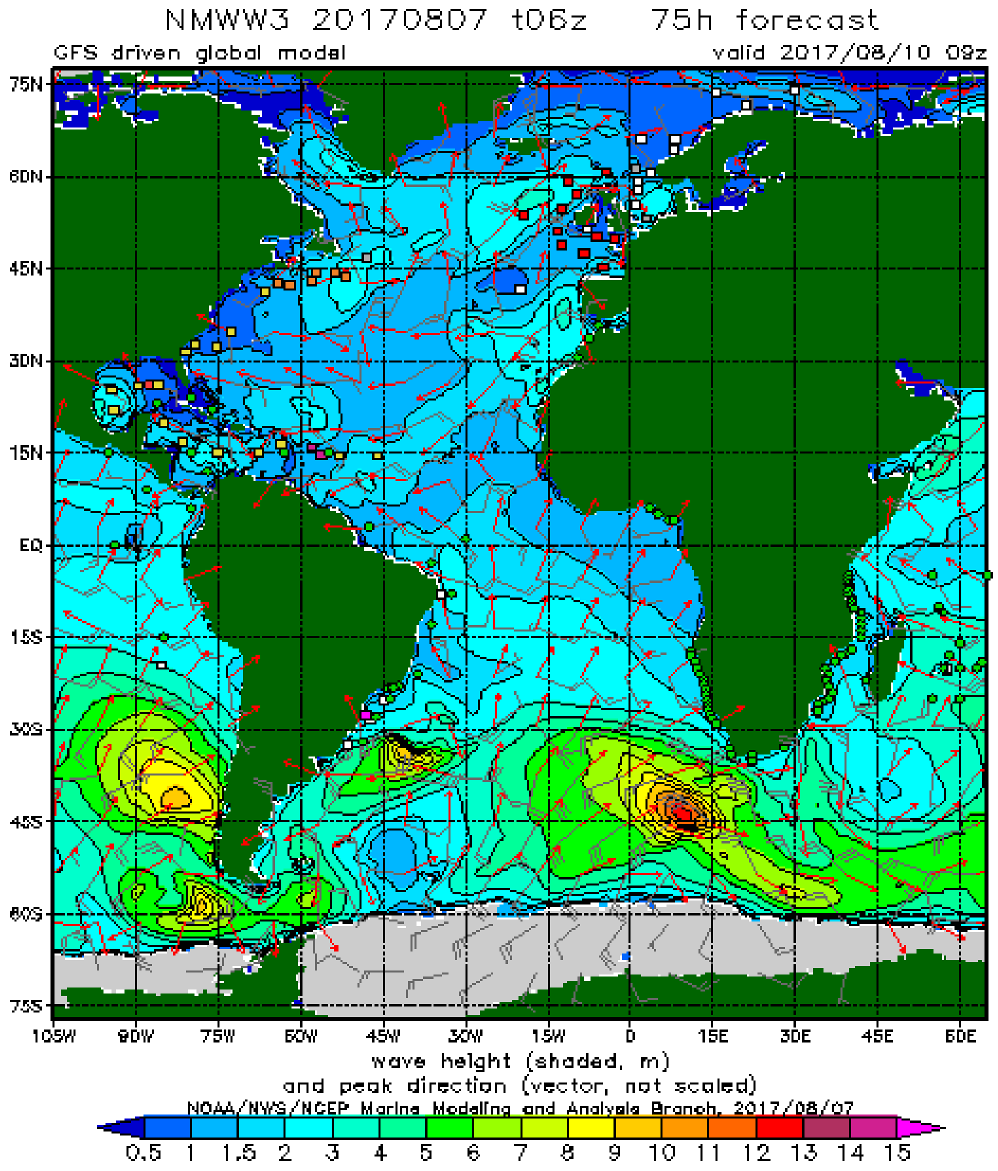
HiGEM - *High Resolution Global Environmental Modelling*



Met Office : Climate Model, expert advice on climate modelling.
Centre for Global Atmospheric Modelling: Atmospheric processes, HPC expertise.
British Antarctic Survey: Polar processes, modelling the cryosphere.
Centre for Ecology and Hydrology: Land surface processes and modelling .
Environmental Systems Science Centre: Clouds and radiation processes, model v satellite data.
Southampton Oceanography Centre: Ocean processes and modelling, remote sensing.
University of East Anglia: Ocean processes and modelling.
British Atmospheric Data Centre: Data management

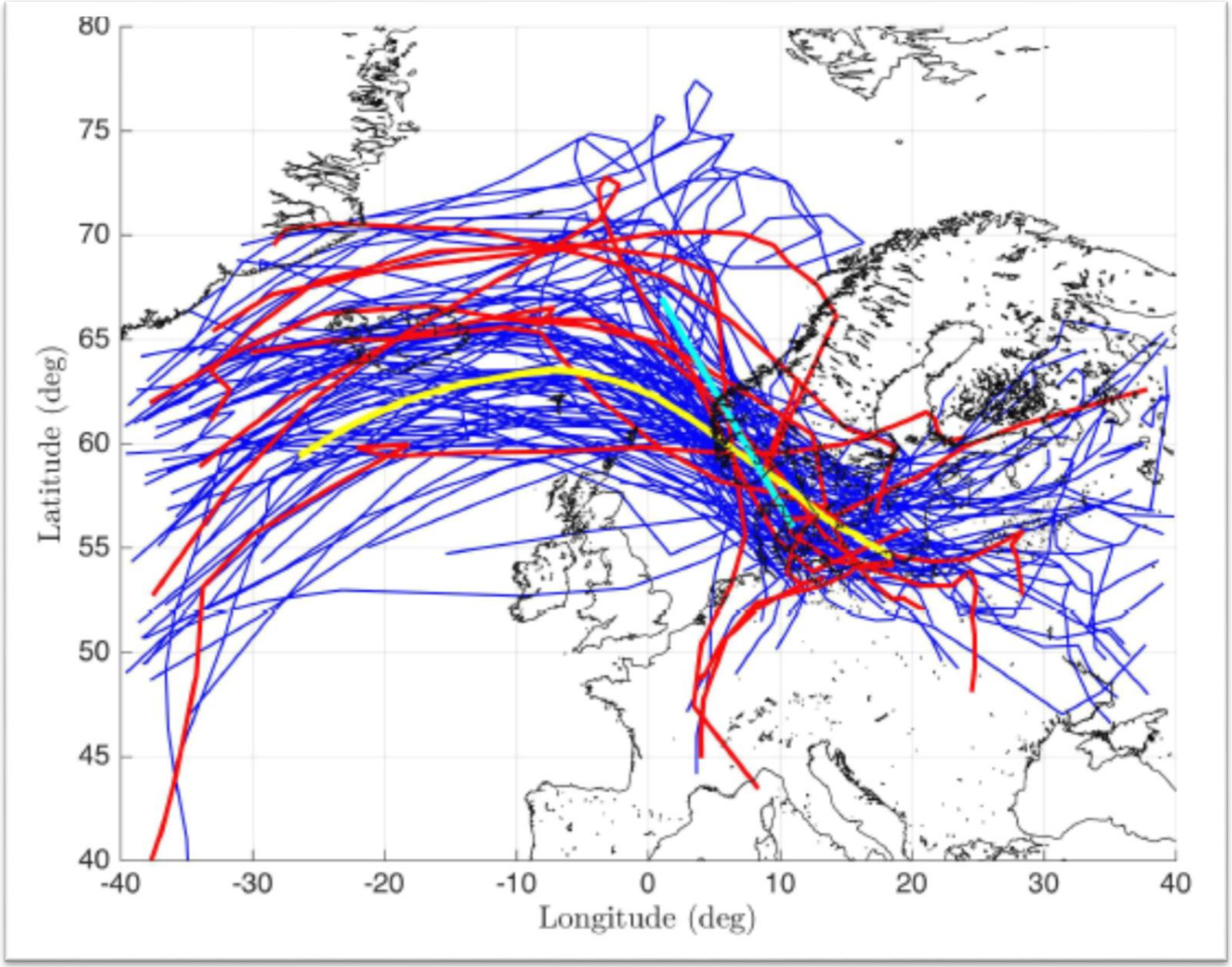
long term P(Hs>h) for non-cyclonic storms

International Association of Oil & Gas Producers



long term P(Hs>h) for non-cyclonic storms

International Association of Oil & Gas Producers

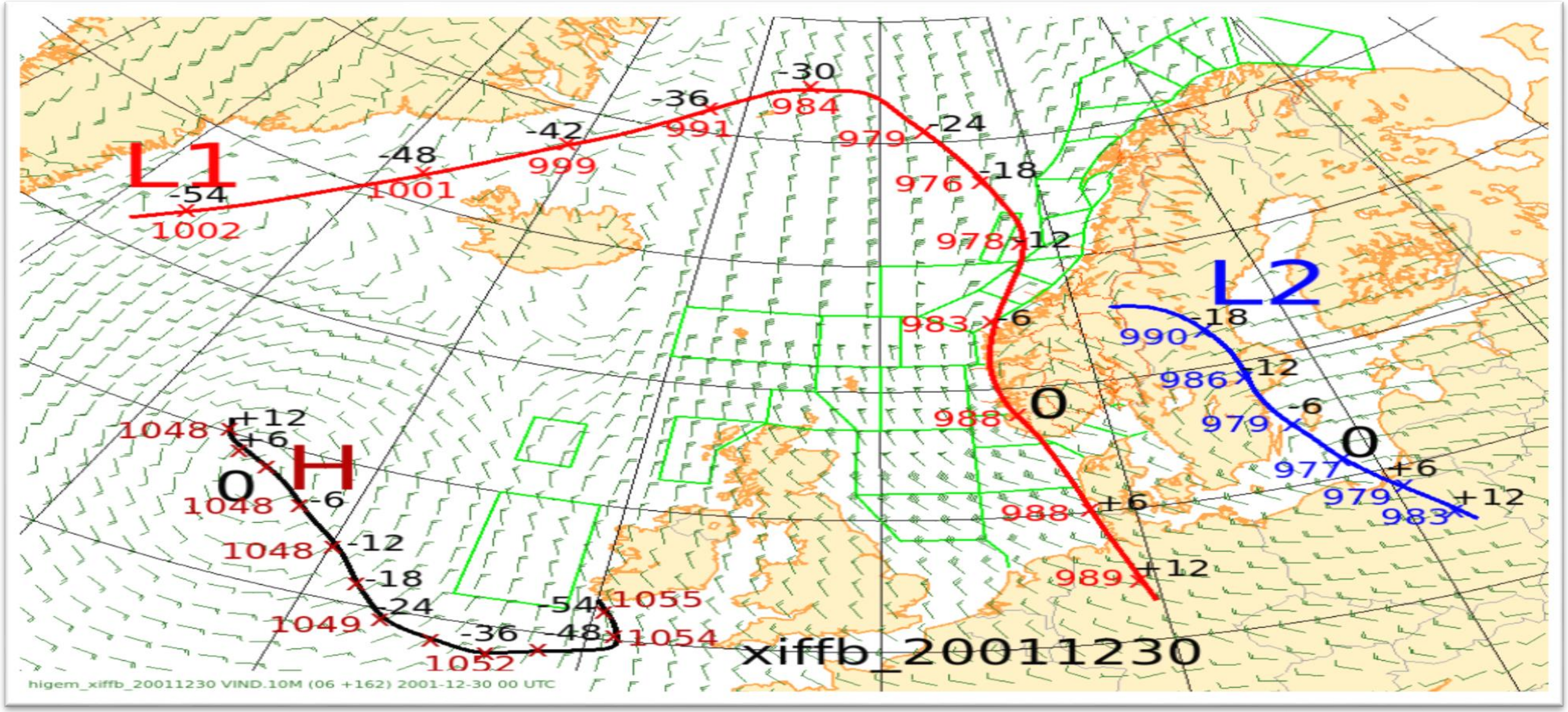


HiGEM wave generating events in North Sea.
top 100 - blue tracks
top 10 - red tracks

Previous data was from 30 years hindcast model

real storm track similar to HiGEM simulation

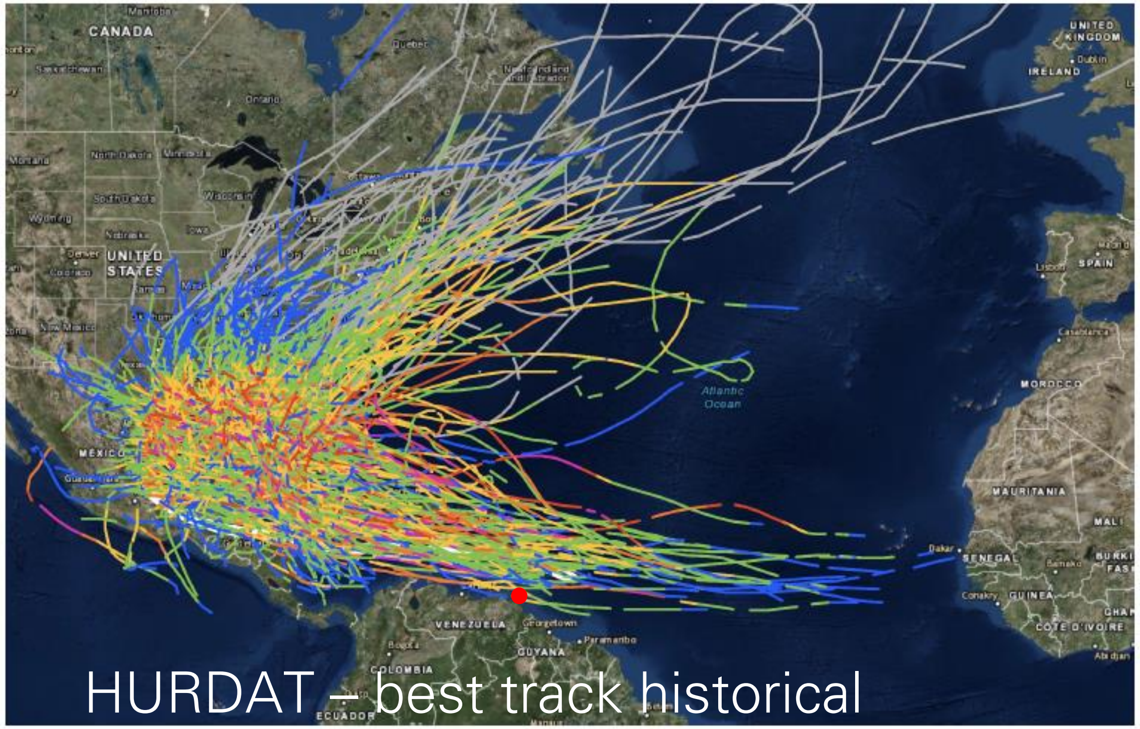
International Association of Oil & Gas Producers

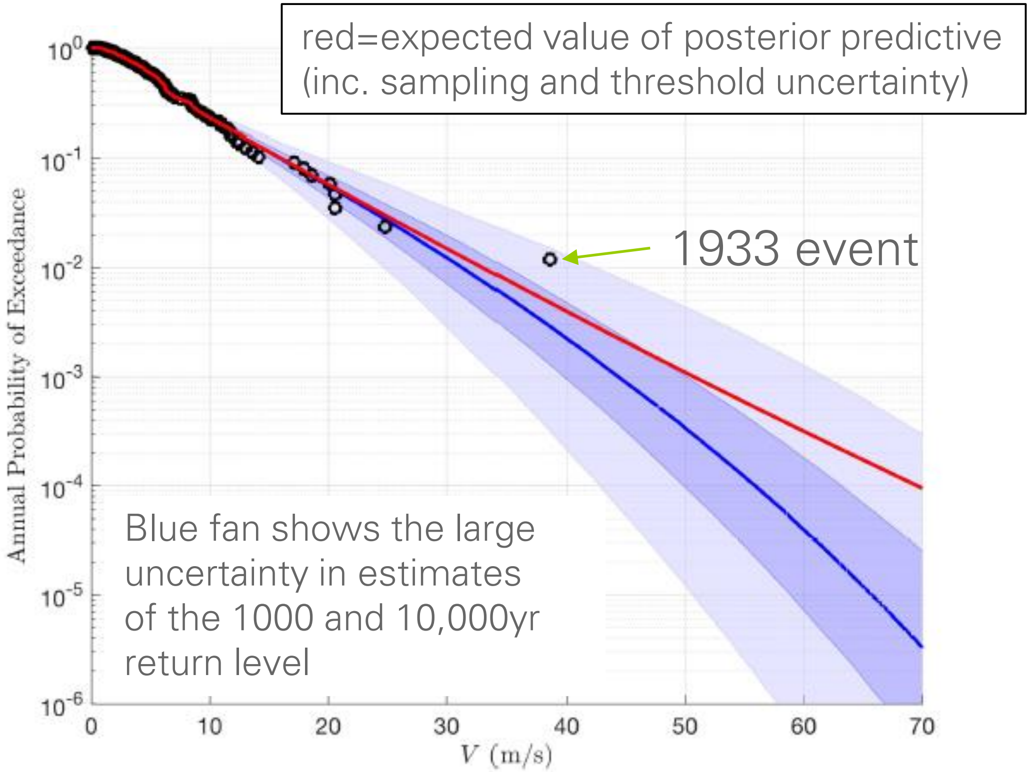


storm track	storm speed	storm intensity	individual wave ht.	individual wave loc.	current magnitude	current direction	tidal level

long term P(Hs>h) for cyclonic storms

severe hurricanes affecting Trinidad are rare but possible.
the historical record is sparse, primarily as a result of Trinidad's low latitude:





long term P(Hs>h) for cyclonic storms - options

Simulation **HadGEM3** -GC31-HM (UK Met Office / Hadley Centre):

- long (330yr) high resolution model simulation of the global climate (present-day C02).
- pressure deficits under-estimated: requires a statistical correction.
- tracks similar to HURDAT, but have some biases: requires some statistical correction.

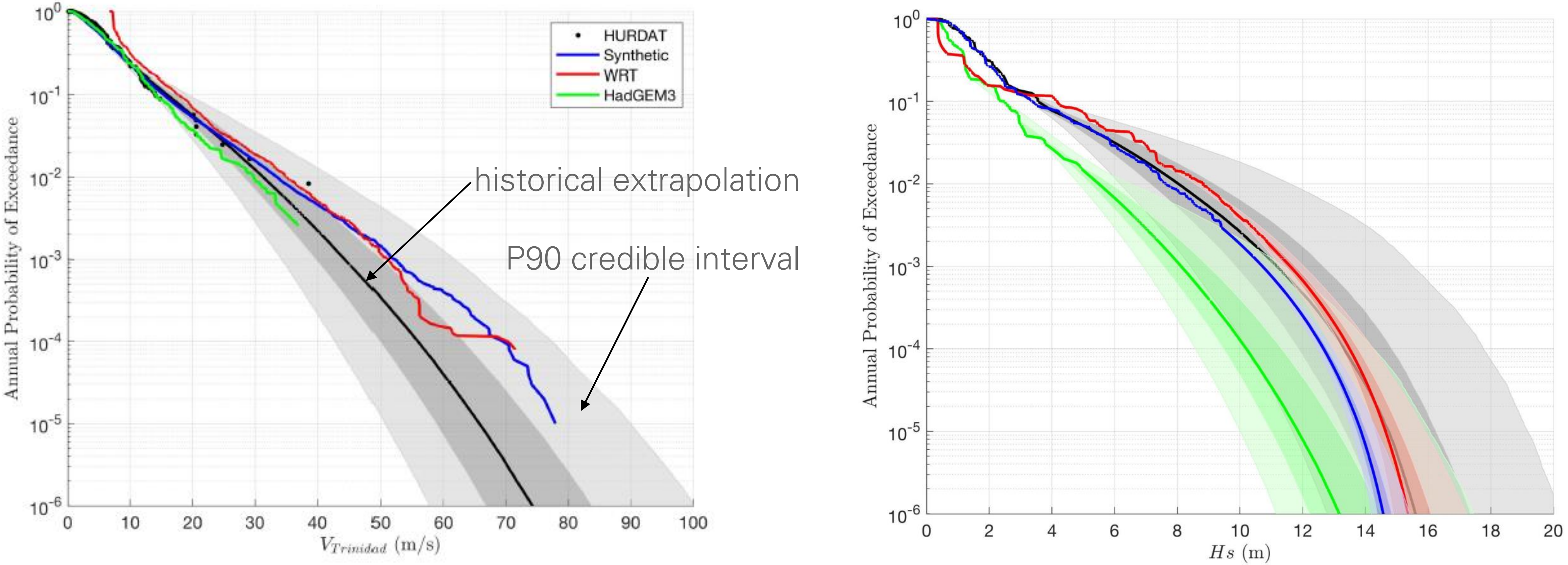
Seeded simulation **WRT** – Wind RiskTech (Kerry Emanuel, MIT)

- seeded tropical cyclones (>100,000) advected by climatology and intensity modelled using CHIPS.
- pressure deficits in good agreement with HURDAT.
- tracks have significant biases compared to HURDAT: requires a statistical correction.

Synthetic (OCG)

- statistical distributions of historical storm data derived.
- empirical distribution of storm tracks with shifting.
- Monte Carlo simulation to produce >100,000 years of storm data affecting Trinidad.

long term P(Hs>h) for cyclonic storms (inc EU)



Recommended approach is to include epistemic uncertainty by weighted combination of the three distributions (HadGEM, WRT and synthetic), where weightings are decided by an expert panel.

Probabilistic Metocean Hazard Analysis (PMHA)

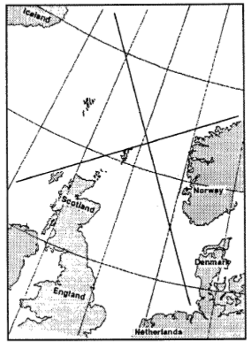
ie calculation of the metocean hazard curve

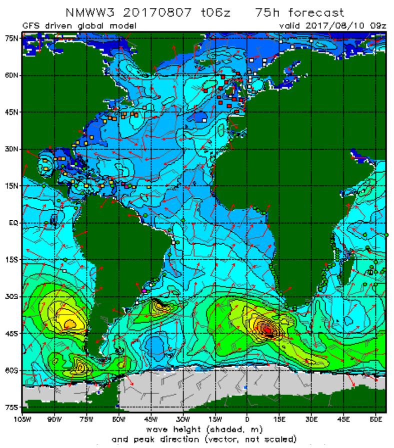
Shell Load Statistics Method (LSM)

Tromans & Vanderschuren 1995

PMHA – LSM - Tromans & Vanderschuren (1995)

$$\text{hazard curve} = v \times \int_{storms} (1 - \text{short term distribution}) \times \text{long term density} \times dl_{mp}$$





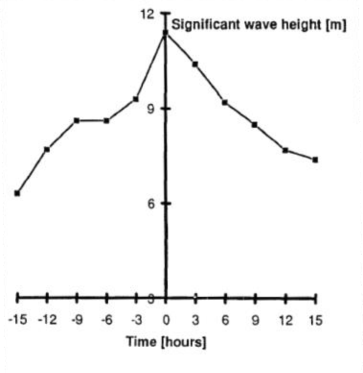
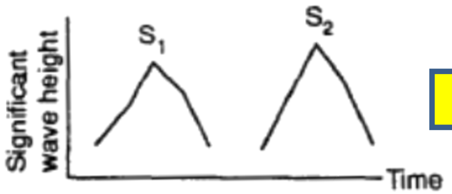


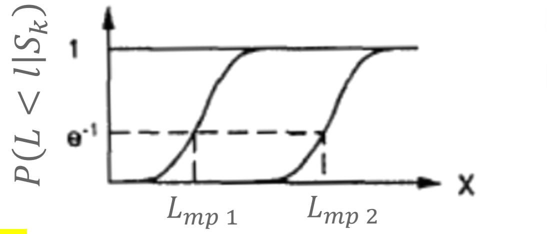
Fig. 1 - A storm history.

STEP 1
Use 25 years of hindcast data of storms by direction and by sea states

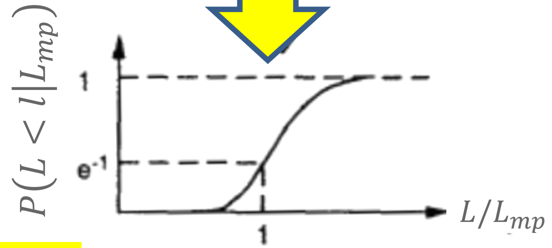
Hindcast data base



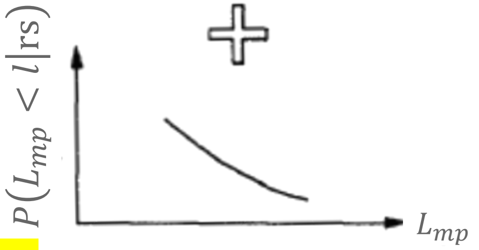
Identify storms



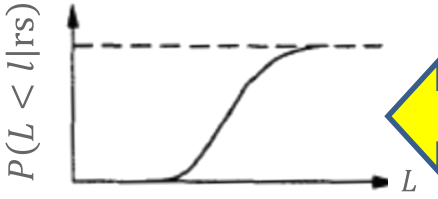
STEP 2 Calculate $P(L)$ and L_{mp} for each storm



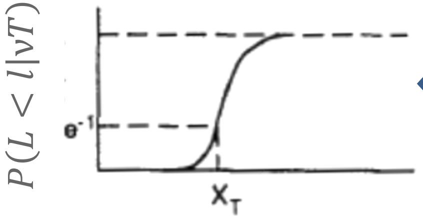
STEP 3 Determine short time variability



STEP 4 Determine long time variability

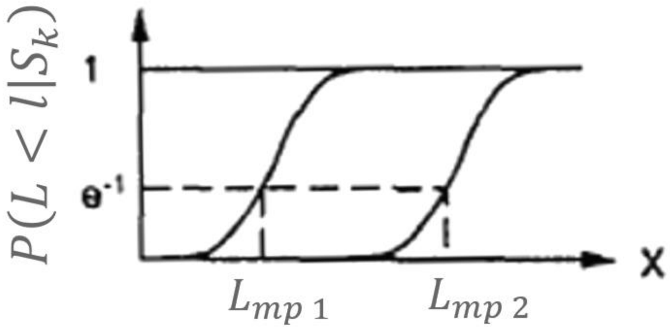


STEP 5 Calculate $P(L < l)$ of any random storm



STEP 6 Calculate $P(L < l)$ of vT random storms

LSM step 2a



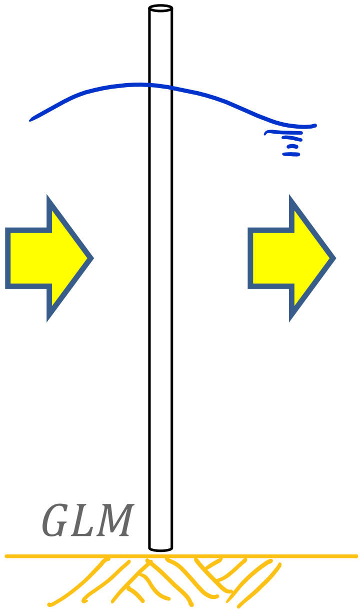
Calculate $P(L)$ and L_{mp} for each storm

n_s storms in the hindcast database
S_k with $k = 1, n_s$ denotes individual storms

k^{th} storm has n_k intervals with constant sea state
I_i with $i = 1, n_k$ denotes individual intervals

i^{th} interval has n_i waves
W_j with $j = 1, n_i$ denotes individual waves

$$\boldsymbol{\theta}_{ij} = \begin{pmatrix} \eta_j \\ \\ T_i \\ \Phi_i \\ u_i \\ \vartheta_{c\,i} \\ W_i \\ \vartheta_{w\,i} \end{pmatrix}$$



$$L_{ij} = l = G(\boldsymbol{\theta}_{ij})$$

$$\boldsymbol{\theta}_{ij} = G^{-1}(l)$$

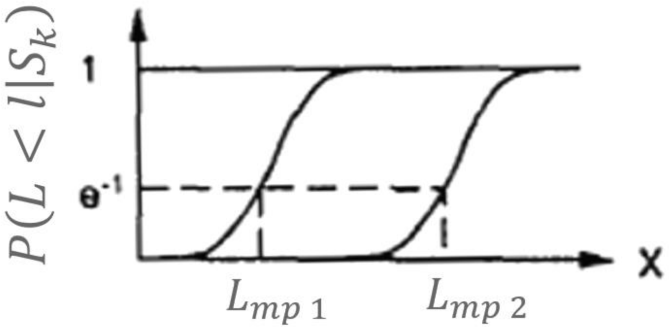
$$\eta_j = \mathbb{G}^{-1}(l) \cong \sqrt{\frac{l}{A_3\Phi_i^2}}$$

$$L_{ij} = G(\boldsymbol{\theta}_{ij}) = A_1u_i^2 + A_2u_i\eta_jT_i\Phi_i cos\vartheta_{c_i} + \boxed{A_3\Phi_i^2\eta_j^2} + \frac{A_4u_i\Phi_i\eta_j^2 cos\vartheta_{c_i}}{T_i} + \frac{A_5\Phi_i^2\eta_j^3}{T_i^2} + A_6\Phi_i^2\eta_j^2T_i^2 + A_7W_i^2 cos\vartheta_{w_i}$$

wave drag below mean water line

LSM has all the structure at the peak kinematics
LOADS includes spatial extent of jacket in the hydrodynamic model
LSM uses deterministic waves (Stokes or NewWave)
LOADS uses steeper breaking waves with lots of aleatory randomness in kinematics v depth

LSM step 2b



Calculate $P(L)$ and L_{mp} for each storm

crest elevations in a stationary sea state assumed to obey a Rayleigh distribution (1995).

for interval I_i with significant wave ht H_{s_i} in storm S_k the probability of a crest elevation E_j of an individual wave (j th wave) not exceeding a given value (η) is

$$P(E_j \leq \eta | H_{s_i}) = R(E_j \leq \eta | H_{s_i}) = 1 - \exp\left(-8\left(\frac{\eta}{H_{s_i}}\right)^2\right) \quad \text{.....(1)}$$

probability of the largest load L_i from the n_i waves in interval I_i exceeding a given value (l) is

$$P(L_i > l | I_i) = 1 - \prod_{j=1}^{n_i} R(E_j \leq \mathbb{G}^{-1}(l) | H_{s_i}) = 1 - \exp\left(-n_i \exp\left(-8\left(\frac{\mathbb{G}^{-1}(l)}{H_{s_i}}\right)^2\right)\right) \quad \text{.....(2)}$$

probability of the largest load L in storm S_k (from the n_k intervals in storm S_k and the n_i waves in each interval I_i where $i = 1, n_k$) exceeding a given value (l) is

$$P(L > l | S_k) = 1 - \prod_{i=1}^{n_k} P(L_i \leq l | I_i) = 1 - \prod_{i=1}^{n_k} \prod_{j=1}^{n_i} R(E_j \leq \mathbb{G}^{-1}(l) | H_{s_i}) \quad \text{.....(3)}$$

proof that $\left(1-\exp(-x)\right)^{n} = \exp(-n.\exp(-x))$

Theorem

$$\lim_{n\to\infty}\left(1+\frac{x}{n}\right)^n = e^x \quad (=\exp(x))$$

Proof.
If $x=0$ then the result clearly holds and if $x \neq 0$ then

$$\begin{aligned}\lim_{n\to\infty}\left(1+\frac{x}{n}\right)^n &= \lim_{n\to\infty}\exp\left(n\ln\left(1+\frac{x}{n}\right)\right) = \lim_{n\to\infty}\exp\left(x\left(\frac{\ln(1+x/n)}{x/n}\right)\right)\\ &= \lim_{h\to 0}\exp\left(x\left(\frac{\ln(1+h)}{h}\right)\right)\\ &= \exp\left(x\left(\lim_{h\to 0}\frac{\ln(1+h)}{h}\right)\right)\\ &= \exp(x)\end{aligned}$$

using the continuity of the exp() function and since $e^0=1$ so $\ln(1)=0$ we have that

$$\lim_{h\to 0}\frac{\ln(1+h)}{h} = \lim_{h\to 0}\frac{\ln(1+h)-\ln(1)}{h} = \frac{d(\ln(x))}{dx}\bigg|_{x=1} = \left(\frac{1}{x}\right)\bigg|_{x=1} = 1.$$

to get from eqn (1) to eqn (2)

$\left(1+\frac{x}{n}\right)^n = \exp(x)$ for large n - see left

let $\frac{x}{n} = -y$ then $x = -\mathrm{ny}$ and $(1-y)^n = \exp(-\mathrm{ny})$

let $y = \exp(-z)$ then $\left(1-\exp(-z)\right)^n = \exp(-\mathrm{n}.\exp(-z))$

consider three hour interval I_i of storm S_k extracted from a time series of met-ocean data. The probability distribution of individual wave height in interval, I_i, which has a significant wave height of H_{s_i}, is, according to Rayleigh,

$$P(E_j \le \eta | H_{s_i}) = R(E_j \le \eta | H_{s_i}) = 1 - \exp\left(-8\left(\frac{\eta}{H_{s_i}}\right)^2\right) \qquad .....(1)$$

if there are n_i waves in interval I_i, then the distribution of the largest of these n_i waves is

$$P(E_j \le \eta | I_i) = \prod_{j=1}^{n_i} R(E_j \le \eta | H_{s_i}) = \exp\left(-n_i \exp\left(-8\left(\frac{\eta}{H_{s_i}}\right)^2\right)\right) \qquad .....(2)$$

proof $\exp(-n.\exp(-\eta))$ = Gumbel distribution for L

International Association of Oil & Gas Producers

assume storm k consists only of 3no. 3hr sea states, each sea state having the same H_s, (ie no of waves in storm k is n_k =3000 approx.) then the crest distribution for the largest wave during storm k is:

$$P\left(E_{lrg} \leq \eta | S_k\right) = \prod_{j=1}^{n_k} R\left(E_j \leq \eta | H_s\right) = \exp\left(-n_k \exp\left(-8\left(\frac{\eta}{H_s}\right)^2\right)\right)$$

approximating the GLM by the largest term only gives $\eta = \mathbb{G}^{-1}(l) \cong \sqrt{\frac{l}{A_3 \Phi_i^2}} = \sqrt{\frac{l}{A}}$

$$\eta^2 = \frac{l}{A}$$

$$H_{mp} = \sqrt{\frac{ln(n_k)}{2}} \cdot H_s$$

$$\eta_{mp(n_k)} = \sqrt{\frac{ln(n_k)}{2 * 4}} \cdot H_s$$

$$H_s^2 = \eta^2_{mp(n_k)} \cdot \frac{8}{ln(n_k)}$$

$$= \frac{l_{mp(n_k)}}{A} \cdot \frac{8}{ln(n_k)}$$

So $$-8\frac{\eta^2}{H_s^2} = -8 . \frac{l}{A} . \frac{A}{l_{mp}} . \frac{ln(n_k)}{8}$$

$$= -ln(n_k) . \frac{l}{l_{mp(n_k)}}$$

$$P = \exp\left(-n_k . \exp\left(-\frac{8\eta^2}{H_s^2}\right)\right)$$

$$= \exp\left(-n_k . \exp\left(-\frac{l}{l_{mp}} . ln(n_k)\right)\right)$$

$$= \exp\left(-\exp(ln(n_k)) . \exp\left(-\frac{l}{l_{mp}} . ln(n_k)\right)\right)$$

$$= \exp\left(-\exp\left(-\frac{l}{l_{mp}} . ln(n_k) + ln(n_k)\right)\right)$$

$$= \exp\left(-\exp\left(-ln(n_k) . \left(\frac{l}{l_{mp}} - 1\right)\right)\right)$$

$$= \exp\left(-\exp\left(\frac{-\left(\frac{l}{l_{mp}} - 1\right)}{1/ln(n_k)}\right)\right)$$

$$= \exp\left(-\exp\left(-\frac{\left(l/l_{mp} - \mu\right)}{\beta}\right)\right)$$

where μ = mode = 1

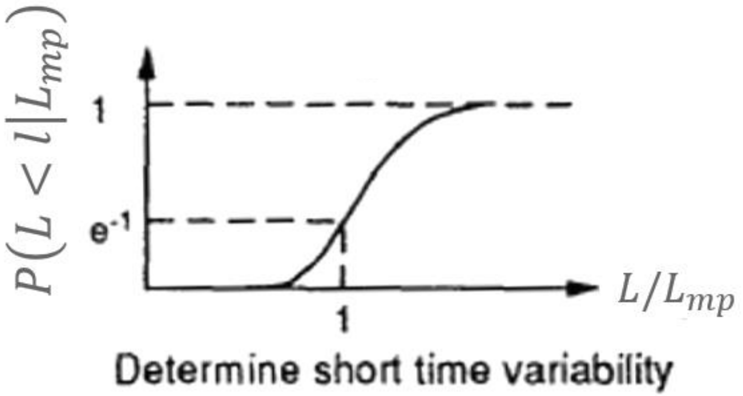
$$\beta = 1/ln(n_k)$$

$$P\left(L \leq l | L_{mp_k}\right) = \exp\left(-\exp\left(-ln(n_k)\left(\frac{l}{L_{mp_k}} - 1\right)\right)\right)$$

$\beta = 1/ln(n_k)$ is the scale parameter

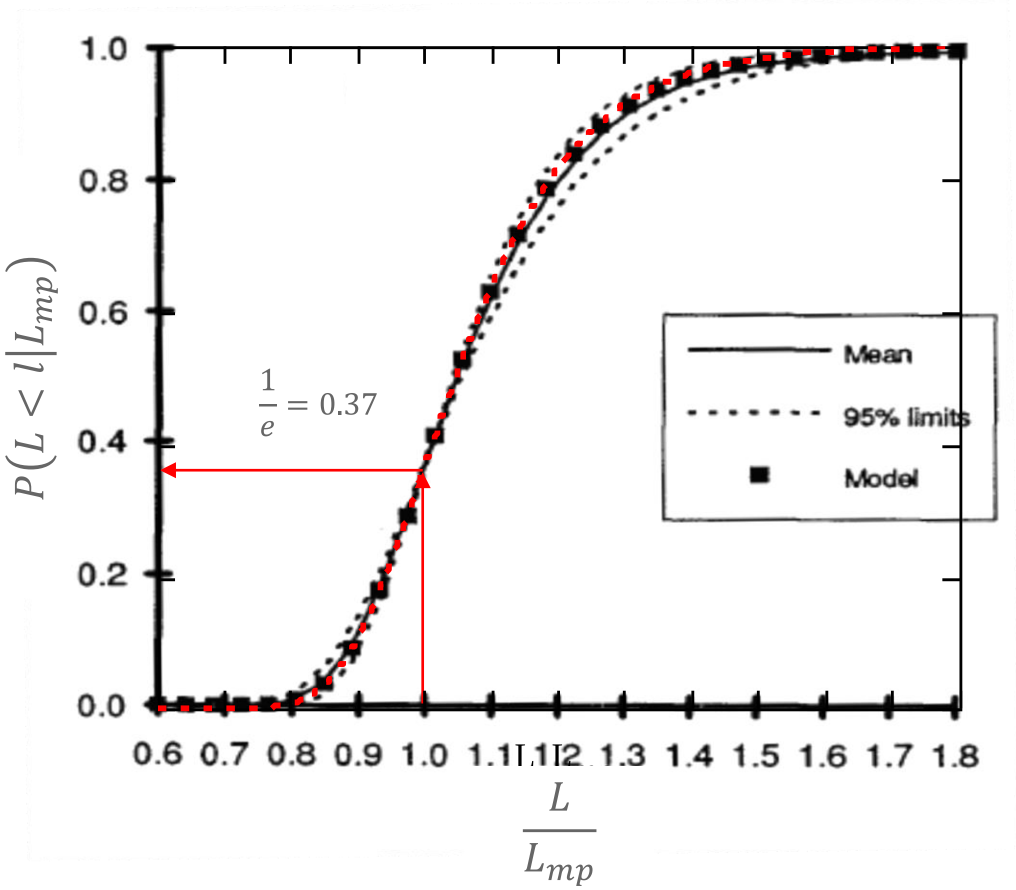
Standard deviation is $\beta\pi/\sqrt{6}$

LSM step 3

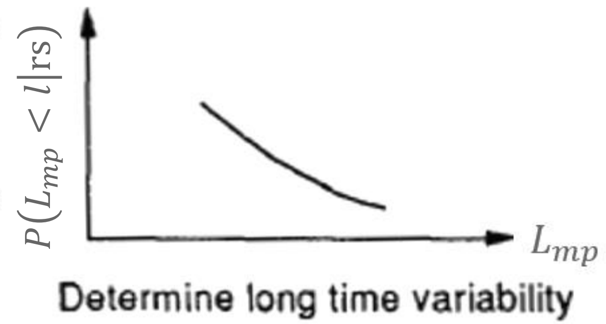


step 2b and the last 2 slides show that the short term distribution for load in ANY given storm, $P(L > l|L_{mp_k})$, converges to the Gumbel distribution (see red dash line) dependent only on the number of waves, N, in the storm:

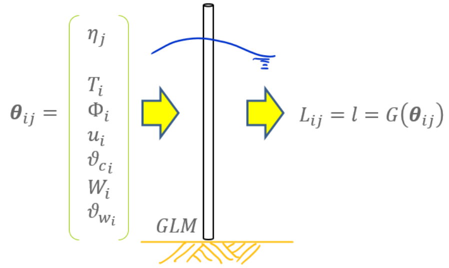
$$P(L \leq l|L_{mp_k}) = \exp\left(-\exp\left(-lnN\left(\frac{l}{L_{mp_k}} - 1\right)\right)\right)$$



LSM step 4



a) convert joint distribution of metocean variables into a single (load) distribution per storm and calculate the most probable value via GLM:



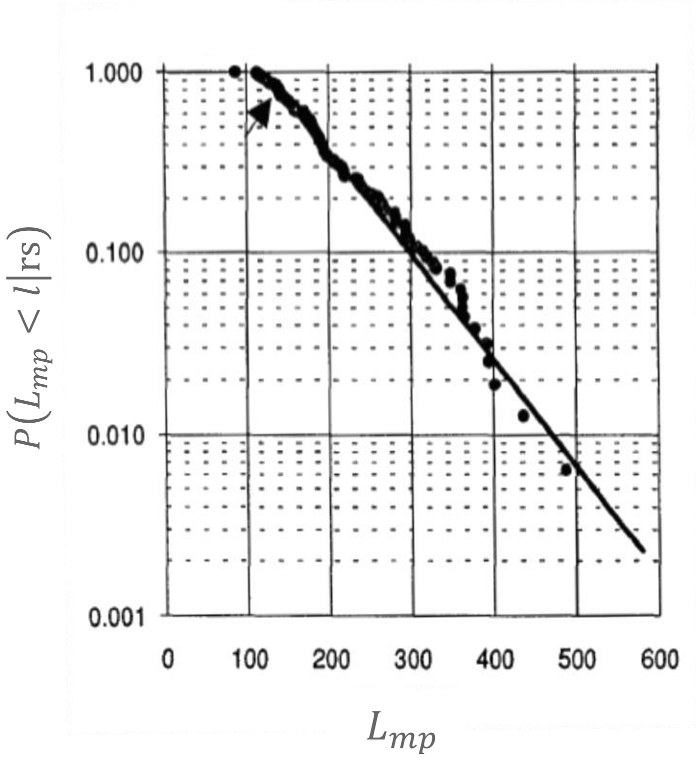
metocean data from 25yr to 30yr hindcast

$$L_{ij} = G(\boldsymbol{\theta}_{ij}) = A_1 u_i^2 + A_2 u_i \eta_j T_i \Phi_i cos\vartheta_{c_i} + A_3 \Phi_i^2 \eta_j^2 + \frac{A_4 u_i \Phi_i \eta_j^2 cos\vartheta_{c_i}}{T_i} + \frac{A_5 \Phi_i^2 \eta_j^3}{T_i^2} + A_6 \Phi_i^2 \eta_j^2 T_i^2 + A_7 W_i^2 cos\vartheta_{w_i}$$

b) fit a assuming a GPD (Generalised Pareto Distribution) or Weibull distribution or exponential distribution:

$$P(L_{mp} \leq l|\mathrm{rs}) = GPD(l, \mu, \sigma, \xi)$$

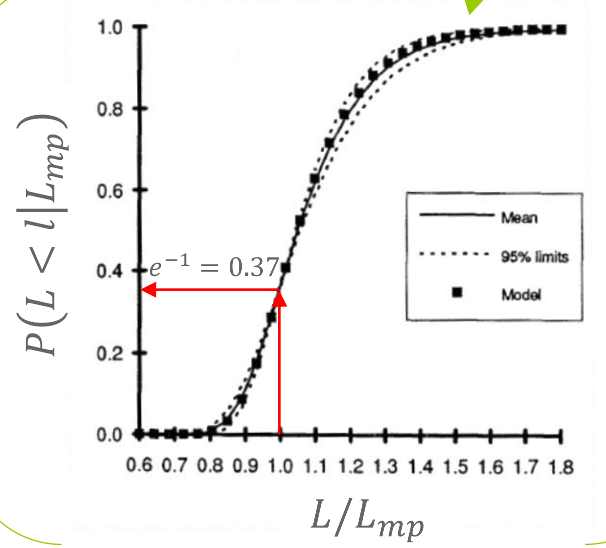
the parameters of the GPD (l, μ, σ, ξ) were determined by minimising the mean square error (MSE) by use of bootstrapping (ie sampling with replacement). Bayesian inference (applied via MCMC) could be used.

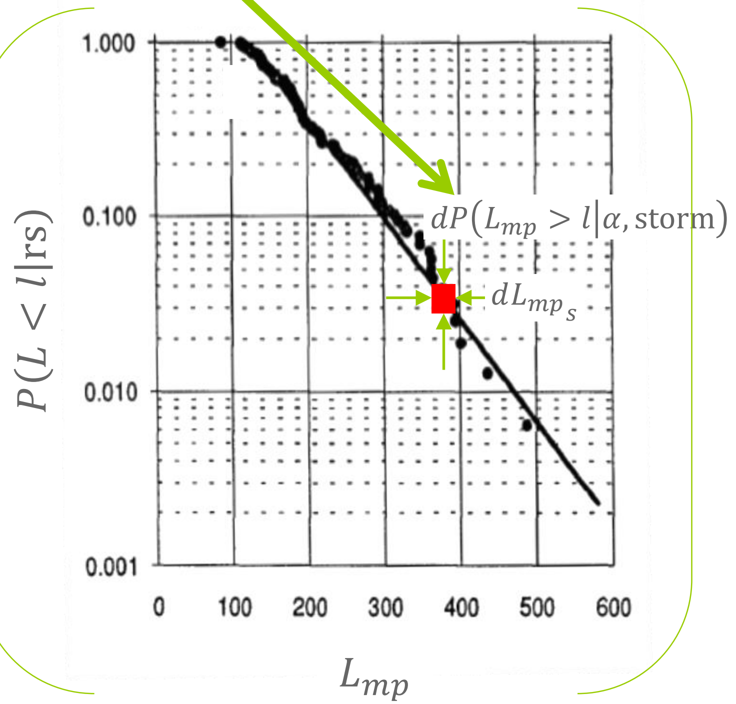


LSM step 5

LSM makes the integration tractable by combining the long-term metocean variables into a single response parameter - the most probable maximum base shear, L_{mp}, over independent storm events.

$$P(L > l|\alpha, \mathrm{storm}) = \int_{L_{mp\,min}}^{L_{mp\,min}} \left[1 - P\left(L \le l \middle| L_{mp}\right)\right] \times p\left(l_{mp}|\alpha, \mathrm{storm}\right) dl_{mp}$$

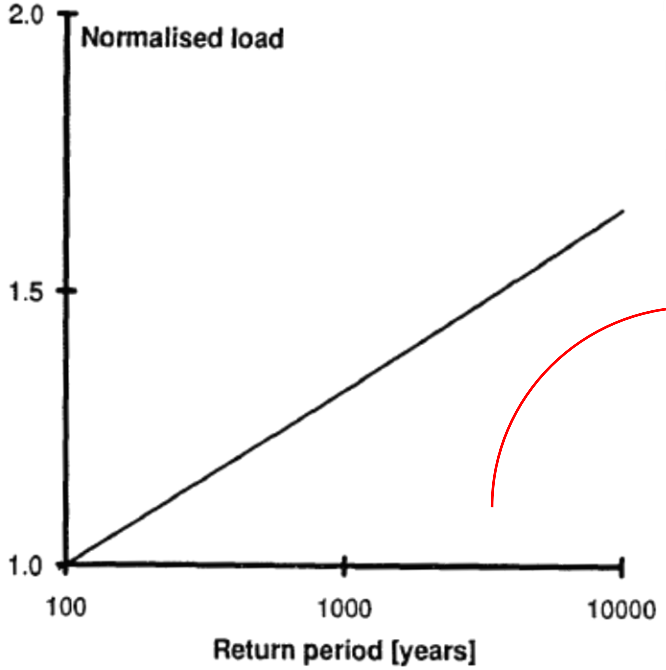


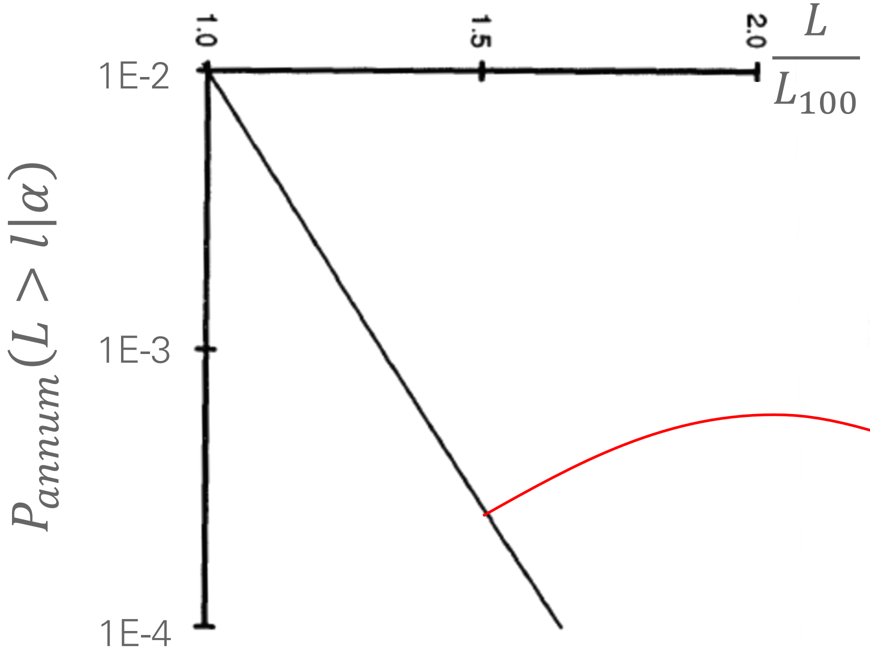


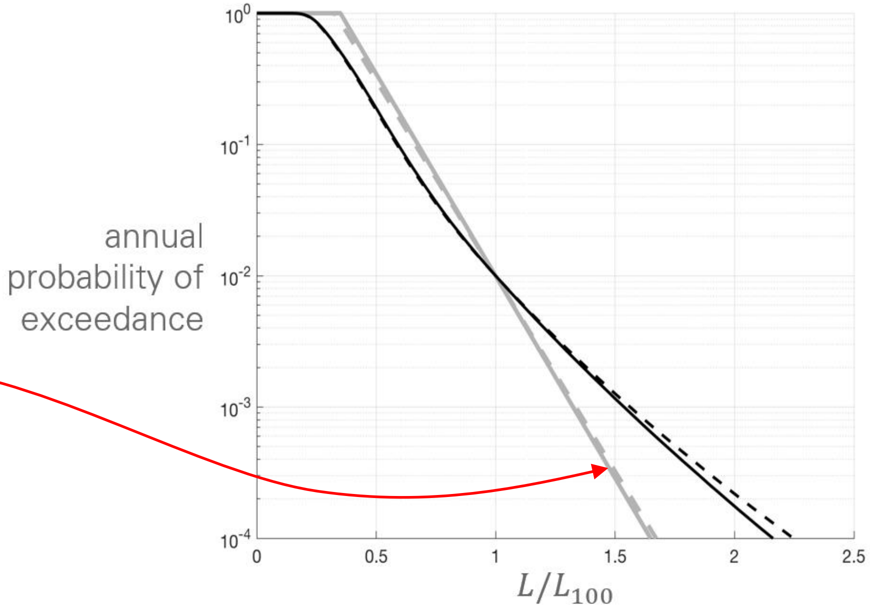
LSM step 6

International Association of Oil & Gas Producers

$$P_{annum}(L > l|\alpha) = \nu_\alpha \times P(L > l|\alpha, \text{storm})$$







LSM step 7

determine metocean parameters to give hydrodynamic load with a return period of 100 years by use of a Stokes 5th wave with height H and period T, an in-line current u and a krf, Φ, that will result in L_{100} when applied to the hydrodynamic model of the jacket

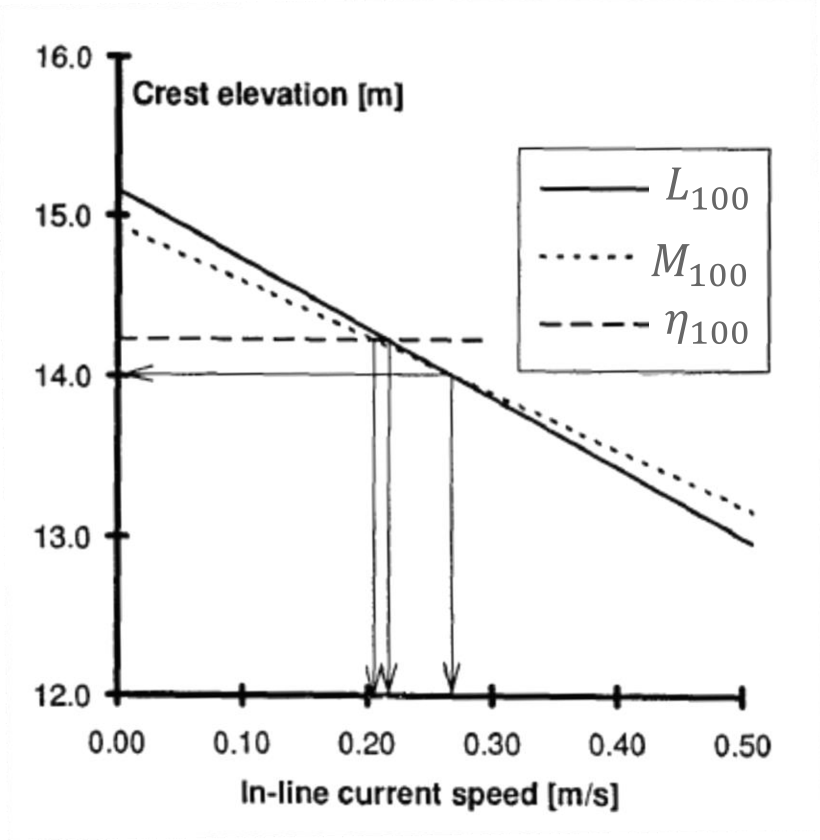
use LSM step1 to 6 to determine $L_{100}, M_{100}, \eta_{100}, H_{100}$ and $H_{mp\,100}$

use correlations to determine T from $H_{mp\,100}$ and η_{100}

use offshore measurements to determine (krf) Φ

then use inverse GLM to determine in-line current that results in hydrodynamic load with a return period of 100 years

$$L_{100} = G(\boldsymbol{\theta}) = A_1 u_i^2 + A_2 u_i \eta_j T_i \Phi_i cos\vartheta_{c_i} + A_3 \Phi_i^2 \eta_j^2 + \frac{A_4 u_i \Phi_i \eta_j^2 cos\vartheta_{c_i}}{T_i} + \frac{A_5 \Phi_i^2 \eta_j^3}{T_i^2} + A_6 \Phi_i^2 \eta_j^2 T_i^2 + A_7 W_i^2 cos\vartheta_{w_i}$$



Probabilistic Metocean Hazard Analysis (PMHA)
ie calculation of the metocean hazard curve

LOADS method/ Gibson & Swan (2020)

(generalisation of the LSM)

storms, profiles, sea states, waves

International Association of Oil & Gas Producers

item 3 item 2

create $p(H_s|\alpha, \text{storm})$ from posterior predictive using MCMC sampling with GPD and H&T approach for joint distribution

randomly sample storms from independent and individual storm events in metocean database

randomly sample significant wave heights from sampled storm

randomly sample metocean covariates from sampled sea state with given significant wave height

randomly sample crests of individual waves from sampled sea state with sampled metocean covariates (stratified MC)

transform linear individual wave to nonlinear surface and kinematics, including wave breaking

embed sampled crest of individual wave in time domain simulation of irregular waves (CRWT)

run hydrodynamic model in time domain to give WiDL(t) and WiJL(t) for individual wave

apply above loads to simple dynamic model of platform to give peak dynamic reaction R (spectral base shear) for individual wave

end sampling of crest of individual waves

create $P\left(R > r \middle| H_{si}, T_{pi}, \gamma_i, \sigma_{\theta i}, \eta_{swli}, u_i, W_i \ldots\right)$ for individual waves in the sampled sea state with the sampled metocean covariates

end sampling of sea state variables

item 1

create $P\left(R_{max} > r \middle| H_s, T_p, \gamma, \sigma_\theta, \eta_{swl}, u, W \ldots\right) = 1 - \prod_{i=1}^{N_{sestate\ samples}} P\left(R \le r \middle| H_{si}, T_{pi}, \gamma_i, \sigma_{\theta i}, \eta_{swli}, u_i, W_i \ldots\right)$ for the sampled sea state

end sampling of sea states from sampled storm

item 1 item 2 item 3

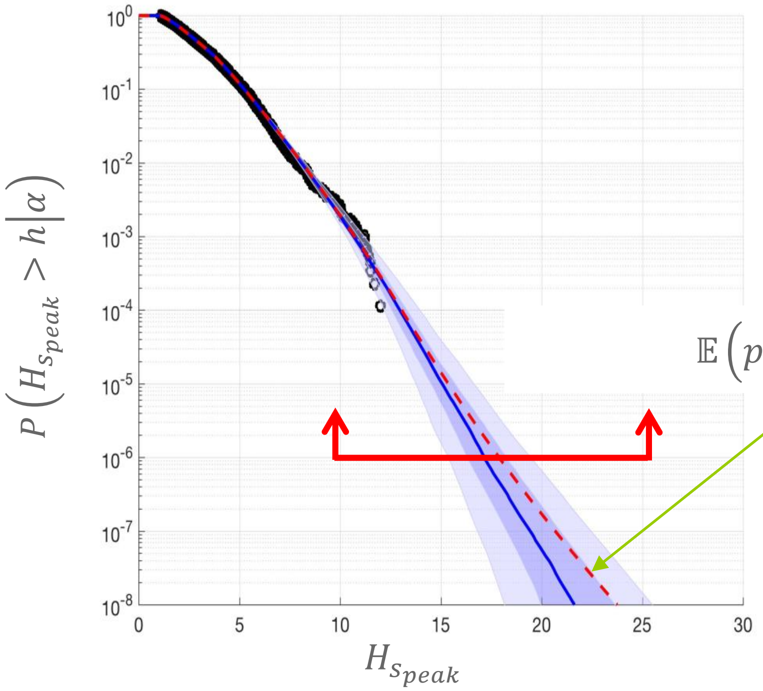
create $P(R_{max} > r|\text{storm}_k) = \int_0^\infty \int_0^\infty \ldots \int_0^\infty P\left(R_{max} > r \middle| H_s, T_p, \gamma, \sigma_\theta, \eta_{swl}, u, W \ldots\right) \times p\left(T_p, \gamma, \sigma_\theta, \eta_{swl}, u, W \ldots \middle| H_s\right) dT_p d\gamma d\sigma \ldots \times p(H_s|\alpha, \text{storm})\, dH_s$

end sampling of storms from independent and individual storm events in metocean database

create $P(R_{max} > r|\text{random storm}) = 1 - \prod_{k=1}^{N_{storms}} P(R_{max} \le r|\text{storm}_k)$ for any random storm

create $P_{annual}(R_{max} > r|\alpha) = \nu \times P(R_{max} > r|\text{random storm}, \alpha)$

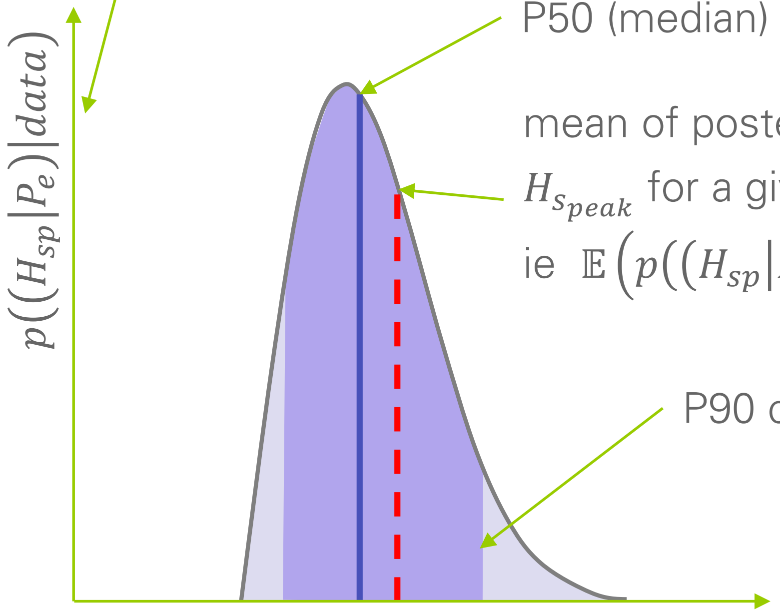
LOADS - steps 1 and 2



$\mathbb{E}\left(p\big((H_{sp}|P_e)\big|data\big)\right)$

mean, median and credible interval of posterior predictive density of $P\left(H_{s_{peak}} > h\middle|\alpha\right)$

$$p\left(\left(H_{s_{peak}} > h\middle|P\left(H_{s\,peak} > h\middle|\alpha\right)\right)\middle|h_{s_{peak}\,data_i\,(i=1,N)}\right)$$



P50 (median)

mean of posterior predictive density of $H_{s_{peak}}$ for a given value of $P\left(H_{s\,peak} > h\middle|\alpha\right)$ ie $\mathbb{E}\left(p\big((H_{sp}|P_e)\big|data\big)\right)$

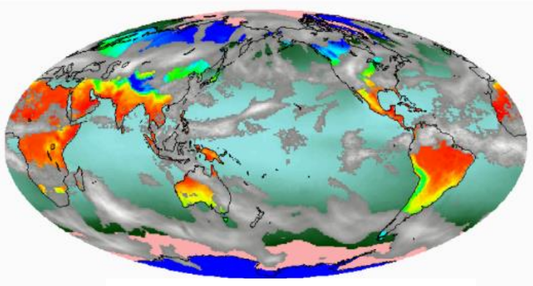
P90 credible interval

$H_{s\,peak}$ for a given value of $P\left(H_{s\,peak} > h\middle|\alpha\right)$

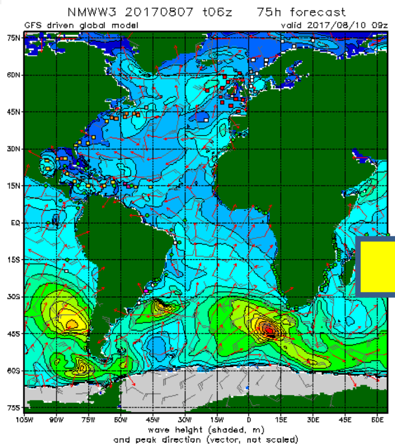
posterior predictive density of annual probability $H_{s_{peak}}$ >15m

LOADS - steps 1 to 4

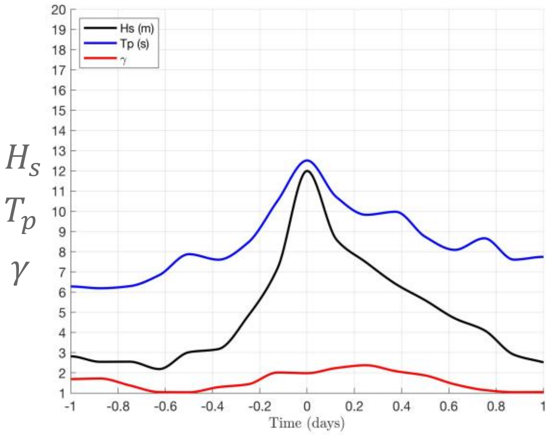
International Association of Oil & Gas Producers

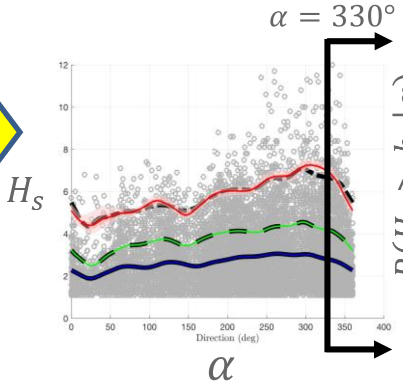


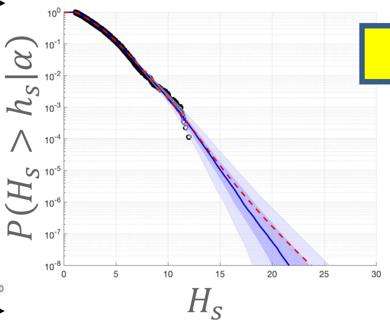
1200 years of wind fields

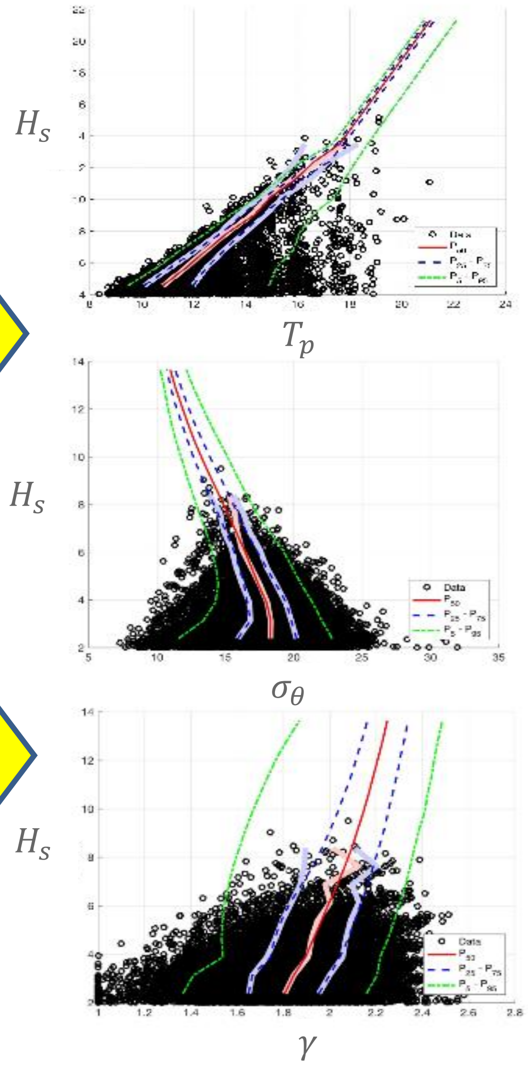


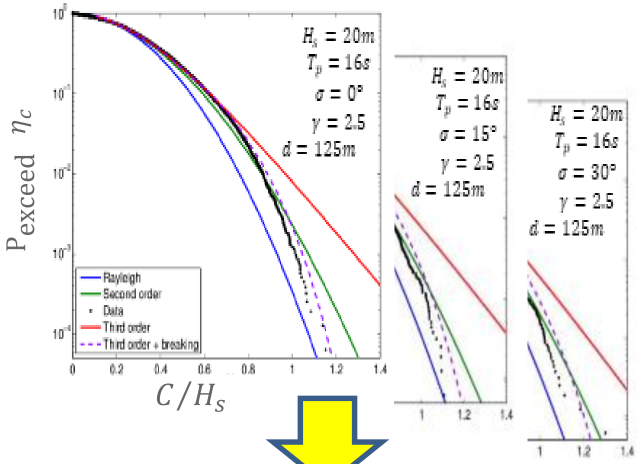
1200 years of Hs and sea state parameters by storm

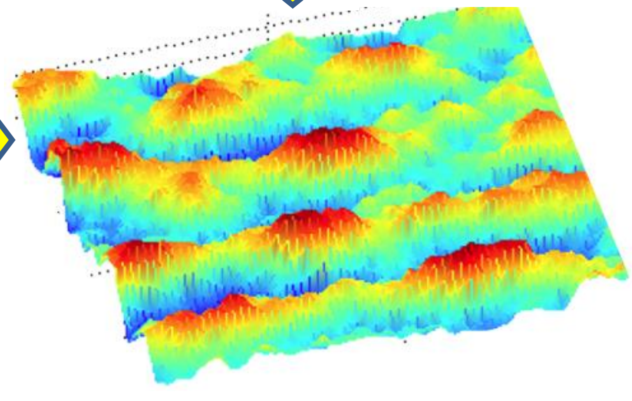












120 sec simulation of constrained random wave kinematics and profile over spatial extent of jacket

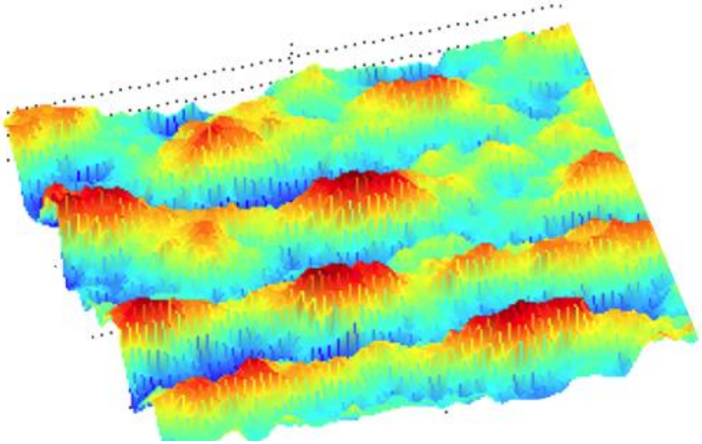
STEP 1
Create long-term data from hindcast or by simulation (eg 1200 years of storms).

STEP 2
Use MCMC to fit long-term distribution of $P(H_s > h_s|\alpha)$
Steps 2 & 3 dev. by Shell-Lancaster

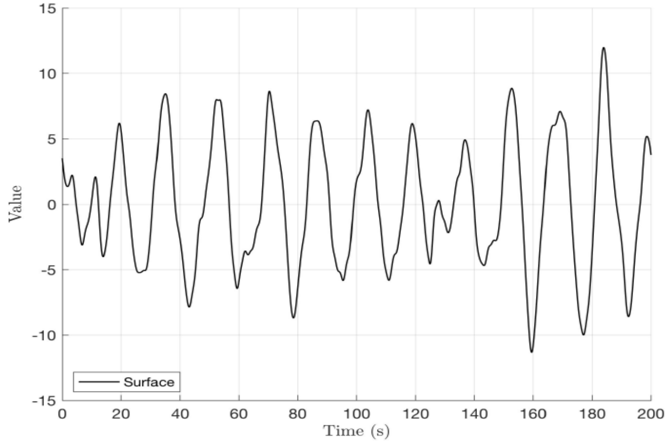
STEP 3
fit joint distribution to simulated data using H&T to get $p(T_p, \sigma_\theta, \gamma, \eta_{swl}, U, W \ldots)|H_s)$

STEP 4
Storm by storm simulation, sample by sea states in a storm from joint distribution $p(T_p, \sigma_\theta, \gamma, \eta_{swl}, U, W \ldots)|H_s)$
Crest ht and wave steepness constrained in random sea state simulation. Linear random irregular simulation with correction for effects $> O(2)$

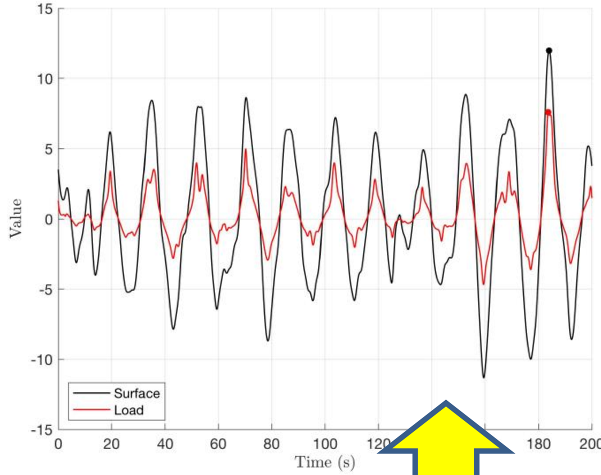
LOADS - steps 4 to 6



120 sec simulation of constrained random wave kinematics and profile over spatial extent of jacket

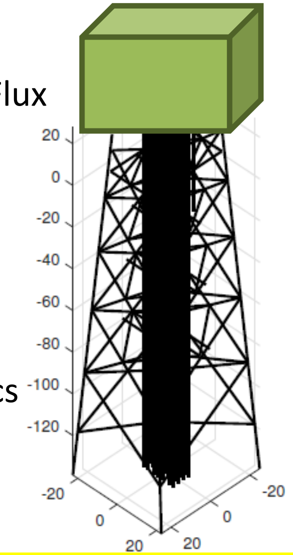


STEP 4
Storm by storm simulation, sample by sea states in a storm from joint distribution $p(T_p, \sigma_\theta, \gamma, \eta_{swl}, U, W \ldots)|H_s)$
Crest ht and wave steepness constrained in random sea state simulation. Linear random irregular simulation with correction for effects $> O(2)$

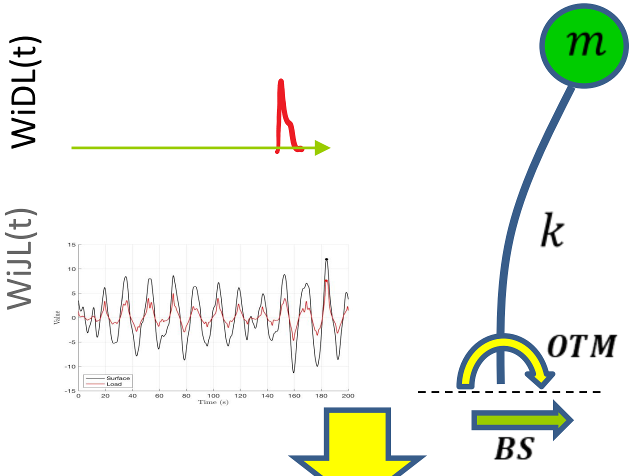


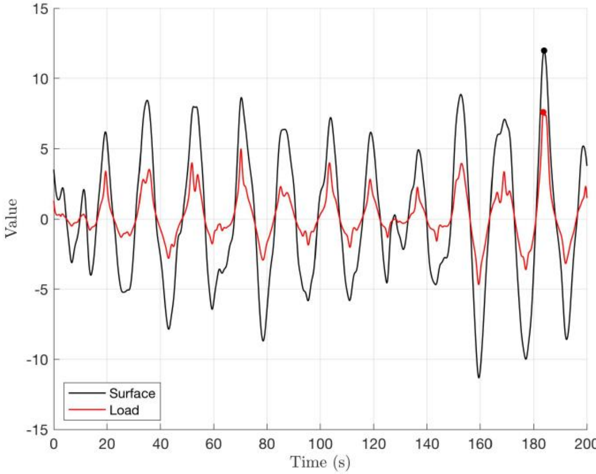
WiDL
Momentum Flux

WiJL
Morrison
with
2[nd] order
kinematics



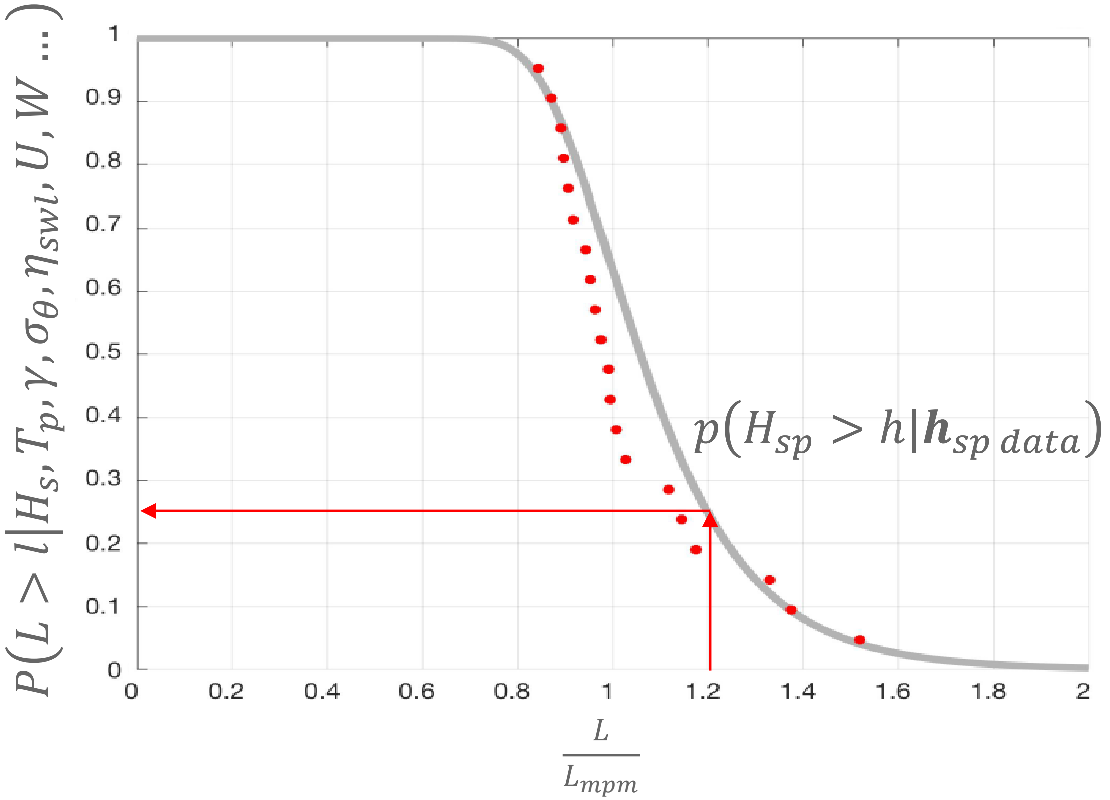
STEP 5
Use hydrodynamic models of jacket and deck to convert kinematics and profile into time history simulation of WiJL and WiDL





STEP 6
Use SDOF dynamic model of the platform to dynamically amplify time history simulation of WiJL and WiDL to produce "spectral base shear"

LOADS – step 7



STEP 7
Determine $P\left(L > l \middle| H_s, T_p, \gamma, \sigma, \eta_{swl}, U, W \ldots\right)$
by fitting to simulated max load

this plot is the short term exceedance of max load GIVEN a sea state

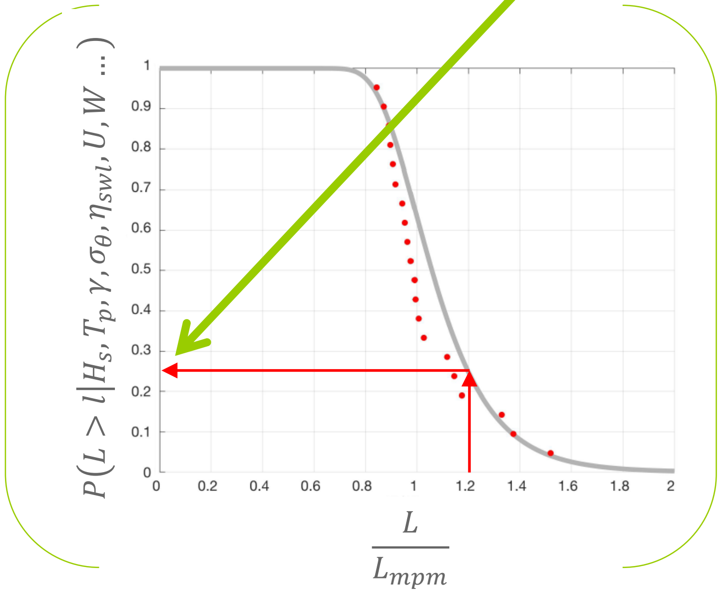
repeat steps 4 to 6 for many samples of Hs and steepness constraints

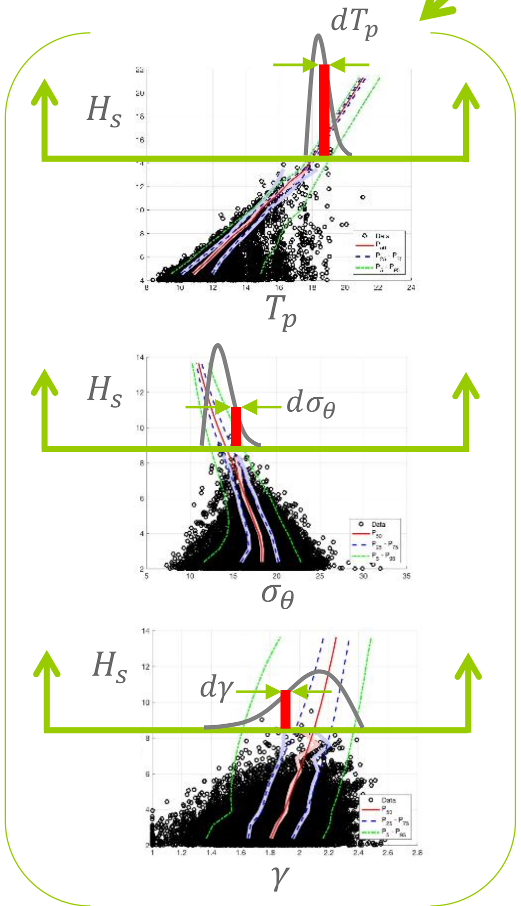
determine probability of exceedance of WiJL (+WiDL) $P\left(L > l \middle| H_s, T_p, \gamma, \sigma, \eta_{swl}, u, W \ldots\right)$ using max load per simulation (red dots)

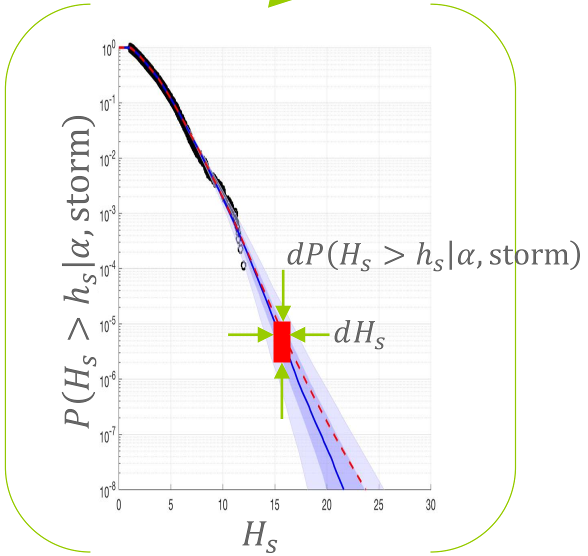
repeat for many samples of sea states

LOADS – step 8

$$P(L > l|\alpha, \text{storm}_k) = \int_0^\infty \int_0^\infty \dots \int_0^\infty P(L > l|H_s, T_p, \gamma, \sigma_\theta, \eta_{swl}, u, W \dots) \times p(T_p, \gamma, \sigma_\theta, \eta_{swl}, u, W \dots |H_s) dT_p d\gamma d\sigma \dots \times p(H_s|\alpha, I)\, dH_s$$

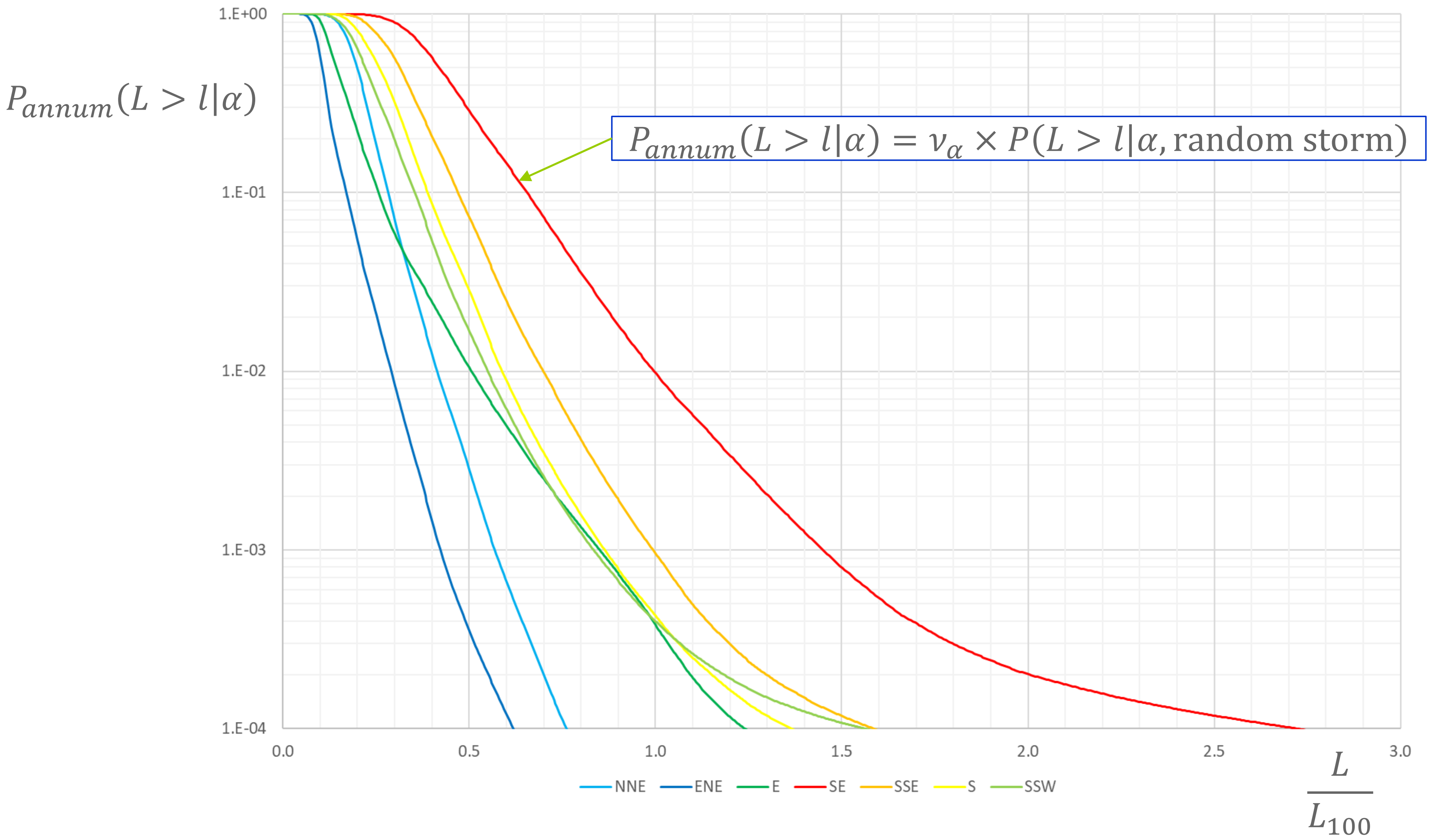






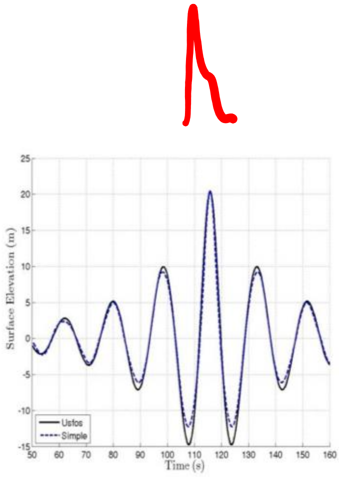
STEP 8
Perform convolution integral by stratified MCS with LHS , MDA and radial basis functions to determine $P(L > l|\alpha, \text{storm})$

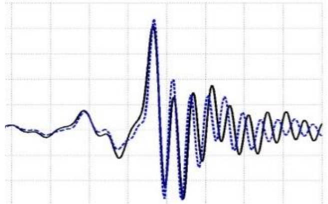
LOADS – step 9

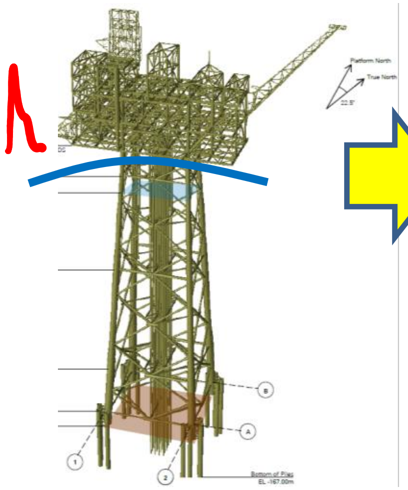


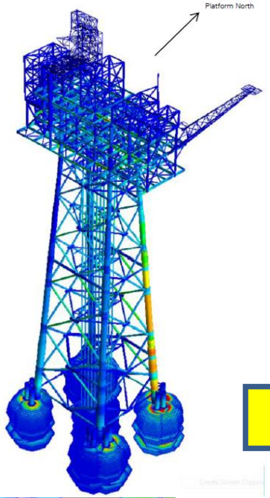
STEP 9
Use storm arrival rate (by direction) to determine $P_{annum}(L > l|\alpha)$

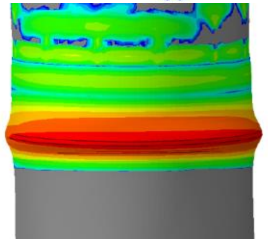
LOADS – steps 10 to 14



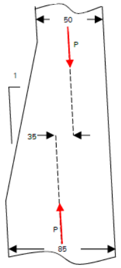


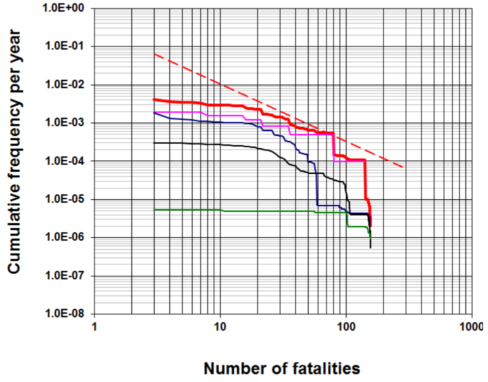


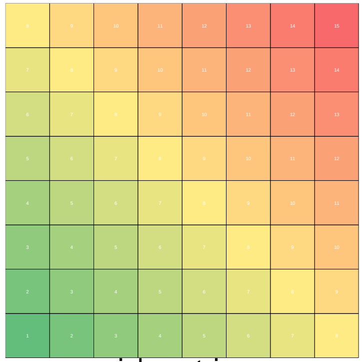




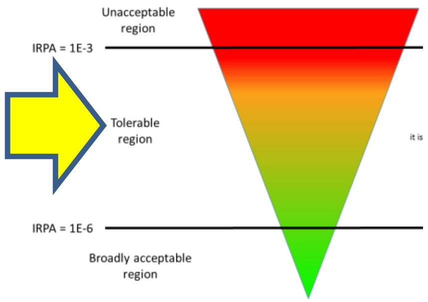
leg D/t=100







risk matrix



Step 10
Deaggregate hazard curve at RP to give (unfocused) wave and WiDL

Metocean & Structural Engineer

Step 11
Determine collapse load - USFOS time history analysis (THA) (dynamic pushover)

Structural Engineer

Step 12
Reduce collapse load if failure mode is pancake leg. Calculate $P_{collapse}$

Structural Engineer

Step 13
Determine IRPA and TRIF given Pcollapse

Safety Engineer

Step 14
Demonstrate L-S risk and B-R is tolerable & ALARP (or apply mitigation measures)

Safety and structural Engineer

ISO 19901-1 (100yr conditions & 10k conditions)

19901-1 cl 5.3 Selecting appropriate parameters for determining design actions and action effects

a) Specified return-period wave height (significant or individual) with "associated" wave period, wind and current velocities. A similar methodology can be applied where a parameter other than wave height dominates the action effect.

b) Specified return-period wave height combined with the wind speed and the current velocity with the same specified return period, all determined by extrapolation of the individual parameters considered independently. This method has been used in the North Sea and many other areas of the world, normally with a return period of 50 years or 100 years. A modified version, using the 100-year wave height and the 100-year wind speed combined with the 10-year current velocity, has been used in Norway.

c) 'Response-based analysis' which requires any "reasonable" combination of wave height and period, wind speed and current velocity that results in— the global extreme environmental action on the structure with the specified return period, or — a relevant action effect (global response) of the structure (base shear, overturning moment, floater displacement, etc.) with the specified return period.

If there is not a strong correlation between waves and current or if the global environmental action is not wave-dominated, then there is no explicit confirmation method a) will approximate to the return-period global environmental action on a structure. By contrast, method c), when correctly applied, will always provide a good estimate of the specified return-period global environmental action.

ISO 19902 (100yr conditions)

International Association of Oil & Gas Producers

19902 cl 9.4.1 Procedure for determining $\boldsymbol{E_e}$

The most general approach for correctly estimating E_e due to combinations of wind, waves and current is via the calculation of the long-term statistics of global metocean actions. (such as applied base shear or overturning moment)

The statistical distributions thus obtained represent response-based global metocean actions.

Based on these long-term statistical distribution(s), a particular combination of wind, wave and current parameters can be identified that is most likely to generate the 100 year extreme global metocean action(s), in conjunction with a corresponding partial action factor, $\gamma_{f,E}$, that provides adequate protection against failure under metocean actions in an extreme storm.

ISO 19901-1 (10k conditions)

International Association of Oil & Gas Producers

5.7 Extrapolation to extreme and abnormal conditions

Designers require metocean parameters at (very) low probabilities or recurrence rates, e.g. with a return period of 100, 1 000 or 10 000 years. Where data covering such long periods are not available, an extrapolation of existing data is necessary. Many extrapolation methods are used and there is no universally accepted method; expert advice shall be sought. In general, the longer the data set the more accurate the extrapolation will be. In some relatively homogeneous areas, site-pooling of hindcast data sets can be used to extend the time basis for estimating return period values at a particular site, thereby reducing the uncertainty of the extrapolation. Important considerations in site-pooling are to choose sites which are far enough apart such that they provide independent realizations of the local conditions, but not to choose sites which are so far apart that true spatial variations in extremes are smoothed over. However, even with long data sets, estimates of (very) low probability parameters can still depend to a considerable degree on the extrapolation method and sampling variability. Confidence intervals can be estimated to assess the uncertainty due to sampling variability.

ISO 19901-1 individual wave

International Association of Oil & Gas Producers

19901-1 cl 8.4.1 regular (periodic) waves

For determination of actions by individual waves on structures, a nonlinear periodic wave theory **may** be used with a calibrated loading recipe. Calibrated loading recipes for drag-dominated structures are coded in typical loading software. Stokes 5th wave theory is commonly used for these types of structure.

As an alternative to periodic wave theories, representative waves from a random sea derived with wave theories such as New-wave theory **may** be used. The New-wave is a representation of the most probable waveform of an extreme wave in a linear random sea.

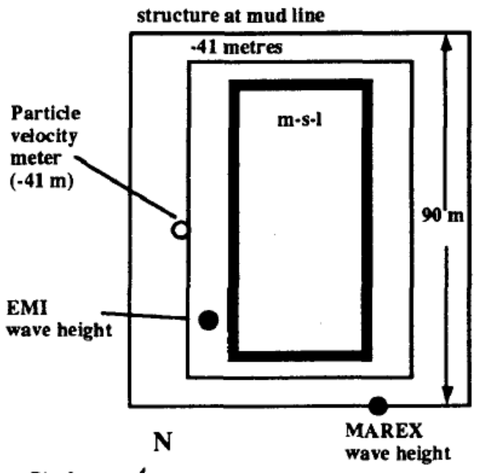
In addition, realistic representation of ocean waves is possible with fully nonlinear numerical wave models, but their use in the calculation of design actions **shall** be calibrated.

19901-1 cl 8.5 Maximum height of an individual wave for long return periods

..... The required long-term individual wave height, H_N, (or crest height) **shall** be established by convolution of long-term distributions derived from these data with a short term distribution that accounts for the distribution of individual wave heights in a sea state. Calculation of the wave in this manner differs from the calculation of the expected maximum wave in a sea state, which normally results in a non-conservative wave height (or crest elevation).

ISO calibrated wave recipe – TERN measurement (1990-1992)

International Association of Oil & Gas Producers



A Joint Industry Project organised by Shell and WS Atkins has analysed the wave loads seen on Shell's Tern platform in the Northern North Sea, between February 1990 and April 1992. Over this period, there were 15 storms with significant waveheight above about 8m, and from each a worst-case 1-hour data record was taken. Within each of these 15 1-hour records, the 25 highest waves were selected - a total of 375 waves in all. Conventional Stokes design waves were then fitted to the height and period of each of these 375 waves, and the peak-to-peak wave load computed on the structure, using a full Morison finite-element model, and exactly following conventional UK design practice. This was compared with the measured peak-to-peak wave load (only oscillatory loads being available, because of the nature of the load sensors), both base shear force (BSF) and overturning moment (OTM), thus giving for each wave the ratio:

$$R_{cycle} = \frac{\text{measured load in single wave}}{\text{computed load in same wave}}$$

ISO calibrated wave recipe – TERN measurement (1990-1992)

International Association of Oil & Gas Producers

Deterministic (R_{cycle})

To increase the data recovery from any individual record a deterministic (wave by wave) analysis is undertaken for the highest 25 cycles to determine:

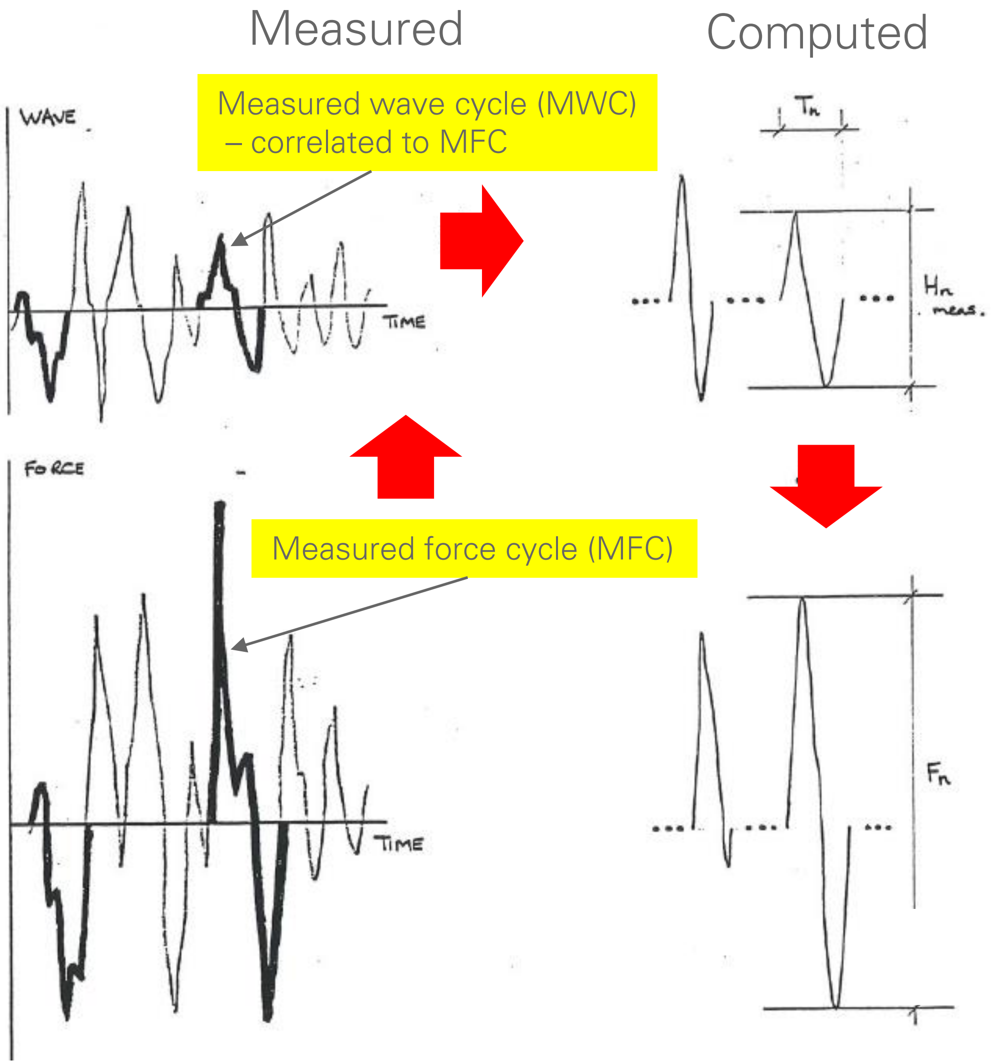
$$R_{cycle} = \frac{\text{Measured Force Cycle}}{\text{Computed Force @ Measured Wave Cycle}}$$

The 'measured wave cycle' corresponds to a correlated measured force cycle (Figure 8.2). The wave cycle zero crossing period used in the computation is the associated measured wave period. To assist in the interpretation of the measured data the set of 25 values have been subdivided into five groups to see if trends exist in the results of:

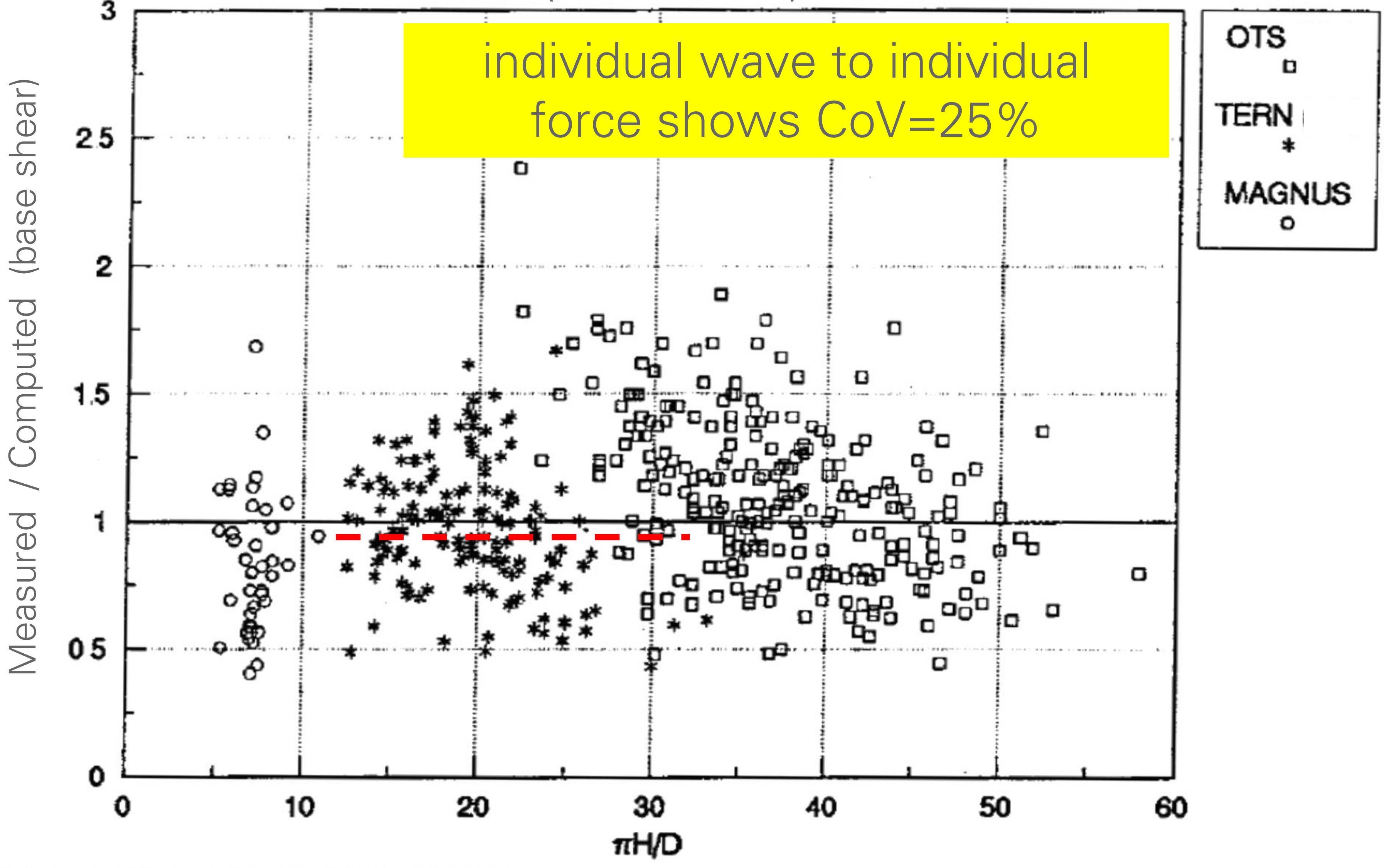
$$R_{avg} = \text{Average of } R_{cycle}$$

$$R_{std.dev} = \text{Standard Deviation of } R_{cycle}$$

H for calculated load = H for the MWC
T for calculated load based on Tz for the MWC



ISO calibrated wave recipe – TERN measurement (1990-1992)



ISO calibrated wave recipe – TERN measurement (1990-1992)

Statistical (R_{stat})

The principal mechanism for comparing the measured and computed values of base shear force (SHR) and base overturning moment (OTM) is the ratio 'R' as defined in the original Study Proposal.

$$R_{stat} = \frac{\text{Measured Maximum Force}}{\text{Computed Force @ Computed Max. Wave Height}}$$

$$\text{Computed Max. Wave Height} = \text{Measured Sig. Wave Height} \times \sqrt{(0.5 \times \text{Ln}\,(3600/T_z))}$$

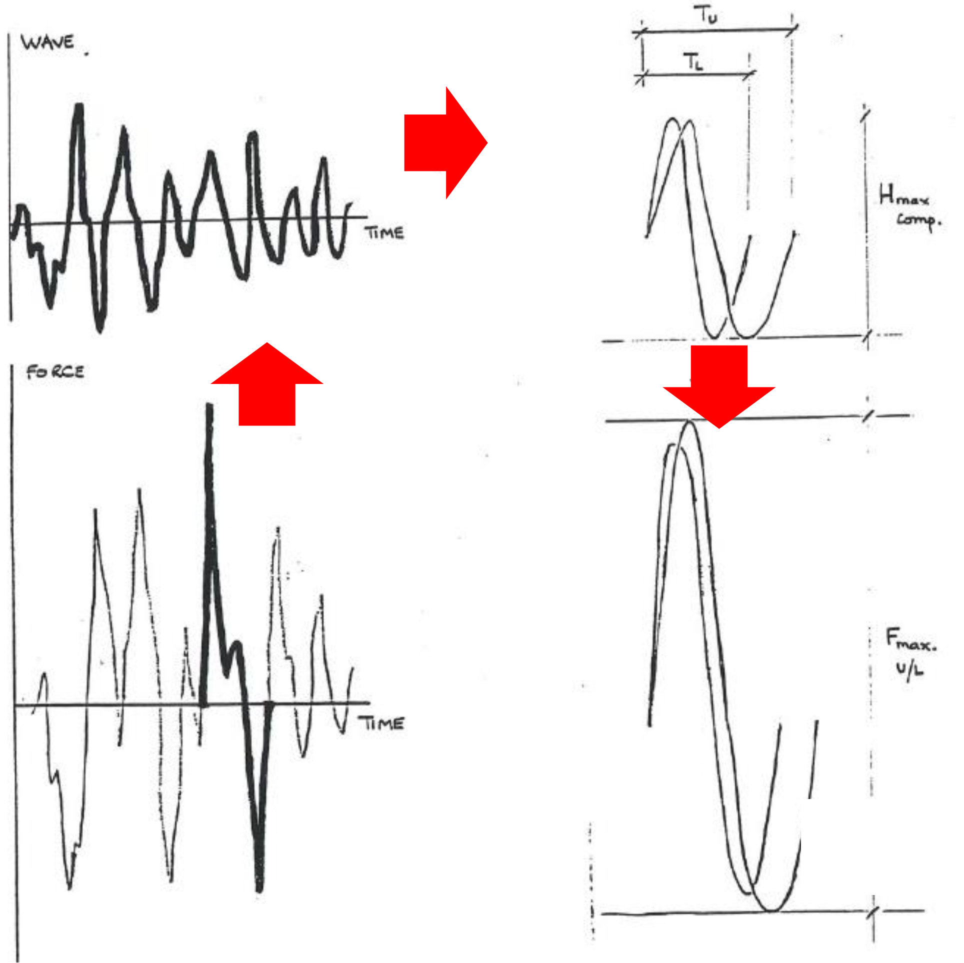
The computed force is taken as the higher of the two load cases derived from the lower and upper (L/U) bound wave periods (Figure 8.1).

Dynamics of fixed marine structures p 256

If an estimate is required for the highest wave in N waves the modal (most probable) value is:

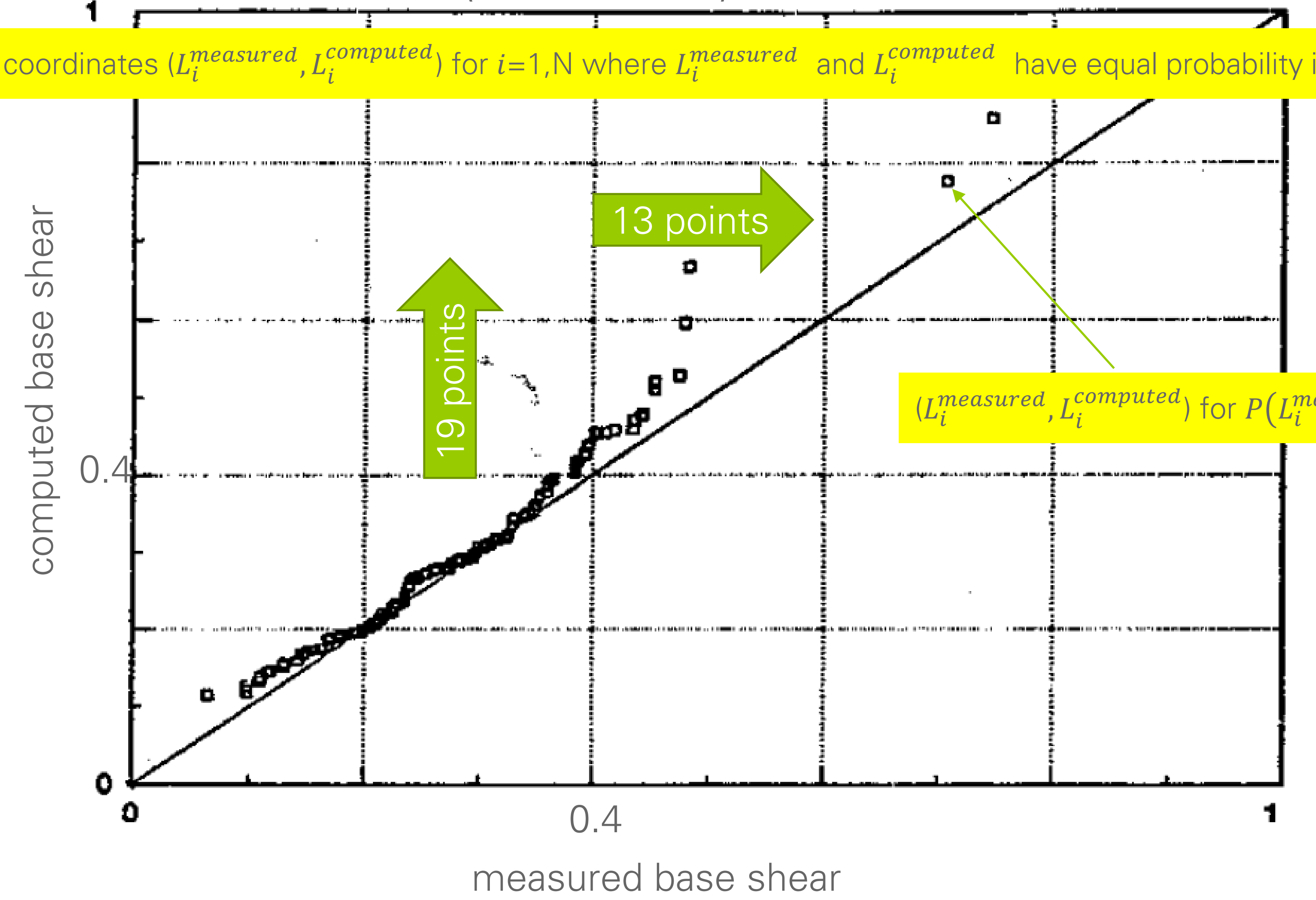
$$H = \sqrt{\frac{\ln(N)}{2}}\, H_s \qquad (6.15)$$

Measured Computed



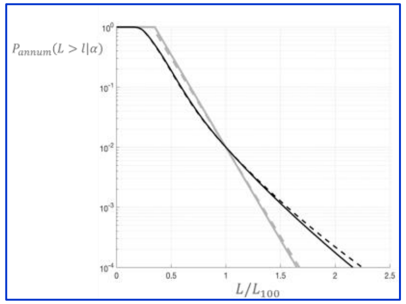
ISO calibrated wave recipe – TERN measurement (1990-1992)

Q-Q plots coordinates $(L_i^{measured}, L_i^{computed})$ for i=1,N where $L_i^{measured}$ and $L_i^{computed}$ have equal probability ie $P(L_i^{measured}) = P\left(L_i^{computed}\right)$



$(L_i^{measured}, L_i^{computed})$ for $P(L_i^{measured}) = P\left(L_i^{computed}\right)$

LSM v LOADS - comparison & points for discussion



LSM

approach complies with ISO 19901-1 and uses an analytical approach to:
- derive short-term response for each storm in database & characterise by a parameter (L_{mp})
- fit distribution of long-term response parameter
- convolute long term L_{mp} distribution with short term distribution of $L_{max} \mid L_{mp}$

1. assumes crests, C, are Rayleigh distributed and load $\propto C^2$
Rayleigh underestimates crest heights but this is not a limitation since more sophisticated models can be/ are used;

2. uses Stokes or NewWave kinematics
underestimates velocities from steep and breaking waves, but again more sophisticated models can be used –
in principle the LOADS short term model could be applied to every sea state in the hindcast and then used in the LSM;

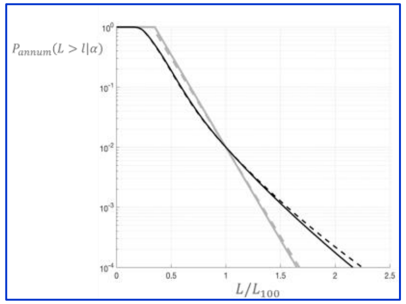
3. constrains extrapolation to an exponential distribution
underestimates epistemic uncertainty from statistical extrapolation but other distributions are used (could use GPD if so desired).
some epistemic uncertainty is included by bootstrapping by can be unstable if not constrained to exponential.

4. converts metocean data to loads with $P_E \cong 10^{-1}$ then extrapolates load to $P_E = 10^{-4}$ by exponential (or any other distribution)
(underestimates load from kinematics in extreme breaking waves)

5. applies dynamic amplification based on design wave
(underestimates dynamic amplification by not convoluting). This is short-term modelling issue – LSM can be adapted to include dynamic response

6. assumes $P(L_{max}|storm)$ converges to the asymptotic form conditional only on L_{mp} , the most probable extreme individual load in the storm.
this is important – fit is done to a parameter describing the max load and a single short-term distribution of extreme response is used in the convolution.

LSM v LOADS - comparison & points for discussion



LOADS

approach complies with ISO 19901-1 and uses a numerical (sampling) approach to:
- fit long-term, joint distribution of storm parameters;
- numerically determine the short-term response in a storm;
- convolute long term distribution of Hs_{peak} with short term distribution of $L_{max}\,|Hs_{peak}$

1. uses crest distributions based on LOADS JIP (extension from ShorTCresT JIP & Maersk tests);
2. uses unfocused irregular waves with nonlinear transformation of surface and kinematics: including wave breaking;
3. uses Bayesian inference with Shell-Lancaster approach (2014) to extrapolate to 10^{-4} per annum;
4. uses a wave by wave approach to calculate extreme load distribution by extrapolating metocean data to $P_E = 10^{-4}$ by H&T then calculating loads with $P_E \cong 10^{-4}$;
5. convolutes dynamic response over all waves and loading events (inc WiD and breaking WiJ);
6. includes aleatory randomness from variability of wave shear profile v depth;
   (LSM could use base shear/OTM response at different levels if required)
7. is compatible with the fragility curve approach ie the aleatory randomness in the wave shear profile (for a given base shear) is available from the MC sampling, can be revealed by deaggregation of the hazard curve, and used to create the fragility curve.

Questions

Dr Ramsay Fraser

Engineering Technical Authority – offshore structures

I&E - engineering

Mobile: +44(0) 7803260300

TEAMS: +44(0)1224 934836

ramsay.fraser@uk.bp.com