Derivation of total extreme water levels using covariate extreme value analysis

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Agenda

- Motivation
- Overview of Covariate Extreme Value (CEVA) approach for storm peaks
- Storm profiles
  - Seastates
  - Surges
- Inclusion of tides
- Simulations within storms
- Return period simulations
- Summary
Motivation

- Wave impact on decks of offshore platforms has a big impact on return period of structural collapse.

- Extent of perceived impact is increasing due to:
  - Increased crest heights due to better understanding:
    - spatial effect across platform area,
    - non-linearities,
  - maybe climate change effects ...
  - Platform subsidence

- For non-evacuated structures can mean platform evacuation in severe storms or even shut down completely.
- In the past, simplistic approaches/assumptions have been used to derive the total water levels in extreme storms.
- Trying to improve the approach ....
Overview of CEVA for storm peak Hs

- Define an array of seasonal-directional bins – typically 32 $Drc (11.25°) \times 24 \ Ssn (~2 \ weeks)$
- Select a storm threshold as a quantile varying across all bins – captures calmer directions/seasons
- Save from each storm:
  - storm peak
  - storm profile (more of this later)
- For all $Drc-Ssn$ bins
  - Select an EVA threshold based on a quantile, $\mu$
  - Fit the storm occurrence rate, $\lambda$, as a Poisson process
  - Fit GP shape, $\sigma$, and scale, $\gamma$, parameters
- Variation of all parameters is by B-splines
- A smoothing parameter defines how quickly their magnitudes can change
- Perform a Monte Carlo analysis for storm peaks for RP
- Identify the largest $Hs$ within each storm and assign to a $Drc-Ssn$ bin
Comparison of modelled and observed storm peaks

- Observed: data - red dots, 95% UI red dashed lines
- Model: median – solid black line, 95% UI black dashed lines
Definition of total water level

Max total water level, $\tau_{WL} =$

- Instantaneous max wave crest
- Hourly mean surge
- Hourly mean tidal level
Storm profiles

It is not sufficient to just base the analysis on storm peaks because ....

- Storms last longer than one sea-state so ...
  - ... largest individual crests may occur during smaller sea states ...
  - ... in a direction sector different to storm peak.

- The \textit{TWL} may occur at a time of
  - ... large tide away from peak $H_s$ ...
  - ... or at a time of large surge.

- So, need to define realistic storm profiles to associate with each storm peak:
  - Want to reflect the variability in characteristics with season, direction and severity of storms
Selection of storm profiles for a simulated storm peak

- Assume that observed storm shapes are representative.

- Put observed “archetype” storm profiles into bins based on their peak $Hs$ and associate $Drc$, $Ssn$

- Find distance, $D$, from any simulated $Hs_{sp}$, $Ssn_{sp}$, $Drc_{sp}$ to each bin

$$D = \sqrt{\frac{(Hs_{sp} - Hs_{bin})^2}{\alpha_{Hs}} + \frac{(Ssn_{sp} - Ssn_{bin})^2}{\alpha_{Ssn}} + \frac{(Drc_{sp} - Drc_{bin})^2}{\alpha_{Dir}}}$$
Storm profiles - waves

Storm archetype

- $H_s$ quantile varying by direction
- Start and end of storm based on $H_s$
  - Storm peak $H_s$

Wave profile use:

- Simulate a random storm peak, $H_{s_{sp}}, D_{rc_{sp}}, S_{sn_{sp}}$
- Find the closest bin to this storm peak, by minimising D
- Randomly select a wave profile from that bin, e.g. profile shown
- Scale the whole profile so $H_s = H_{s_{sp}}$ of a simulated storm
- Modify $D_{rc}$ and $S_{sn}$ to match $D_{rc_{sp}}, S_{sn_{sp}}$
- Modify wave periods, $T_{02}$, to keep the same steepness
Storm profiles - surge

Storm archetype
- Hs quantile varying by direction
- Start and end of storm based on Hs

Surge characteristic values
- Median surge

Surge and wave profiles are selected as a pair from same storm
Modify storm surge profile based on relationships between peak storm Hs and either:
- Surge max, min and median, or
- Surge median and range
**Example – max storm surge versus Hs**

- **Base on:**
  - Max storm $H_s$
  - Max storm surge

- Define an $H_s$ “lock point” as a quantile

- Derive median value of max surge for $H_s$ lock point

- Fit a slope based on linear regression

- Fit to all Drc-Ssn bins in one go using splines to capture variability across array
Storm surge versus Hs – max, min, median by direction

- Storm maximum
- Storm median
- Storm minimum

- Each plot shows range of fits from 4 $D_{rc}$ x 24 $S_{sn}$ bins in each octant
Storm surge versus Hs – max, min, median by month

- Storm maximum
- Storm median
- Storm minimum

Each plot shows range of fits from 32 $Drc \times 2 \ Ssn$ bins in each month
Storm surge versus Hs – range by direction

- Storm range

- Each plot shows range of fits from 4 \( Drc \times 24 \) \( Sn \) bins in each octant
Storm surge versus Hs – range by month

- Storm range

- Each plot shows range of fits from 32 $D_{rc} \times 2 \ S_{sn}$ bins in each month
### Storm surge versus Hs summary

<table>
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<tr>
<th>$H_s$ lock</th>
<th>Slope</th>
<th>Surge lock</th>
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Comparison of observed and predicted storm surge

Maximum

Minimum

Median

Range
Residuals between observed and predicted storm surge

Residuals are sampled during Monte Carlo analysis
Storm surge scaling – based on min, max, median

Archetype storm

\[
S'_{\text{max}} = f(H_{sp}, H_{lock}, surgeLock_{\text{max}}, slope_{\text{max}}) + \text{RandomResidual}_{\text{max}}
\]

\[
S'_{\text{median}} = f(H_{sp}, H_{lock}, surgeLock_{\text{median}}, slope_{\text{median}}) + \text{RandomResidual}_{\text{median}}
\]

\[
S'_{\text{min}} = f(H_{sp}, H_{lock}, surgeLock_{\text{min}}, slope_{\text{min}}) + \text{RandomResidual}_{\text{min}}
\]

Scaled storm profile

\[
\text{scaling}_{>\text{median}} = \frac{S'_{\text{max}} - S'_{\text{median}}}{S_{\text{max}} - S_{\text{median}}}
\]

\[
\text{scaling}_{<\text{median}} = \frac{S'_{\text{min}} - S'_{\text{median}}}{S_{\text{min}} - S_{\text{median}}}
\]
Storm surge scaling – based on range and median

Archetype storm

Scaled storm profile

\[ S'_{\text{min}} = f(H_{s_{\text{sp}}}, H_{s_{\text{lock}}}, \text{surgeLock}_{\text{range}}, \text{slope}_{\text{range}}) + \text{RandomResidual}_{\text{range}} \]

\[ S'_{\text{median}} = f(H_{s_{\text{sp}}}, H_{s_{\text{lock}}}, \text{surgeLock}_{\text{median}}, \text{slope}_{\text{median}}) + \text{RandomResidual}_{\text{median}} \]
Storm surge modelling performance

- Based on:
  - Max, min, median
  - Observed data points (grey)

- Comparison of:
  - observed (red)
  - modelled (black)

- Medians (solid)
- 95% UI (dashed)
Inclusion of tides

- Sample tide
  - In “deep water” by just a random selection
  - In shallow water, tide is sampled from the same storm as the waves, to preserve interactions
Simulation within storms

- $H_{sp}$ simulated with an associated $D_{rcsp}$ and $S_{snsp}$ using varying Poisson and GP distributions
- Randomly-selected archetype storm from the “closest” bin
- Re-scale:
  - entire storm profile $Hs$ to match the peak to $H_{sp}$, $D_{rcsp}$ and $S_{snsp}$
  - wave periods scaled to maintain wave steepnesses
  - surge history using the selected method
- Add tide (or re-using tide, if a shallow-water location)
- Calculate total water depth for every sea state as $\text{tide} + \text{surge} + \text{water depth}$
- Randomly sample $C_{max}$ from each sea state using Forristall distribution based on total water depth
- Calculate the maximum TWL from every sea-state within the storm as: $C_{max} + \text{surge} + \text{tide}$
- For each storm, max value of TWL is saved for every $Drc-Ssn$ bin impacted by storm
Return period simulation

Use Monte Carlo approach to simulate all storms in a RP of interest multiple times:

- Fit Poisson and GP models to $B$ bootstraps of the original data
- Make $R$ realisations of the full return period of interest for each bootstrap
- Produces $B \times R$ simulations
- Save largest values $TWL$ for every $Drc$-$Ssn$ bin
- Produce CDFs for the maxima for RP of interest in each $Drc$ and $Ssn$ bin
- RV for each bin is taken as the most-probable value $\sim\exp(-1)$
- Other percentiles, can also be captured, e.g. 95% UI
10,000-year return values ranges

- Based on ranked storm maxima from all simulations
- The more simulations, the smoother the lines
- This example based on 300 simulations
- The spread reflects uncertainties ....
Uncertainty

- The natural randomness (aleatory uncertainty)
  - Sampling storm peaks multiple times from the fitted model
  - Sampling storm profiles
  - Sampling wave height and crests
  - Re-scaling surge histories from the residuals of the fitted distribution
  - (Sampling tide randomly)

- Uncertainty in model based on finite sample and modelling assumptions (epistemic uncertainty)
  - EVA threshold
  - Bootstrapping the original data multiple times

- Aleatory uncertainty dominates the confidence interval range within CEVA.
# Results

## Wave crest directional return values

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## Wave crest monthly return values

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## SWL monthly return values

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Summary

- Described a process to derive TEWL using the CEVA approach.
- Storm peak modelling based on spline-smoothed: thresholds, Poisson rates, GP parameters.
- Wave storm profiles are sampled and scaled to match peaks of simulated storms.
- Associated storm surge profiles re-scaled using linear regressions and residuals.
- Addition of random or associated tides, depending on water depth.
- Monte Carlo simulation is used based on multiple bootstraps and realisations.

Still under development:
- Better scale storm characteristics to very large storms, e.g. storm length
- Use of Heffernan & Tawn conditional extremes approach to extrapolate surge characteristics to higher $H_s$
- Increasing use of Numerical Integration (rather than Monte Carlo approach)
- Incorporation of more recent wave crest probability distributions