Storm surge flood level modelling during cyclones for Port Hedland

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Acknowledgements

Cardno team

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Organizations who contributed data
>
> Port Hedland Port Authority
> Department of Transport
> Bureau of Meteorology
> Department of Water
> Town of Port Hedland
Presentation Overview

Overview of Port Hedland and context of cyclone risk

Definition of the study aims

Overview of modelling approaches for cyclones in the context of determining cyclonic design water levels

Description of Monte Carlo cyclone track model developed for the Pilbara coast

Application of Monte Carlo cyclone track database in a numerical model system to determine design water levels

Conclusions and areas for further development

Study Site

Pilbara coast has complex physical oceanography

Large tide range ≈ 7.5m at Port Hedland

Port Hedland is the world’s largest bulk export port

200 Mta exported in 2011

Export value in 2011 ≈ $40 billion

*The Pilbara coast experiences more cyclones than any other part of Australia* (BoM)
Port Hedland

Port Hedland Port Developments

UDP - 495Mta

Outer Harbour Capacity - 100 to 400Mta
**Coastal Processes**

Average annual number of tropical cyclones:

![Diagram showing central pressure distribution](image)

**Cyclone Risk and Impacts**

Pilbara coastline experiences high frequency and intensity of cyclones.

Cape Lambert ≈ 150km west of Port Hedland

1939 Cyclone – Photo taken outside Esplanade Hotel storm tide estimated at +5.7m AHD, +2m above HAT.
Storm surge risk assessment in WA is governed by the State Coastal Planning Policy – SPP 2.6.

Prior to recent review, storm surge risk for planning purposes was defined by:
- The passage of a Category 5 cyclone tracking to maximise its associated storm surge.
- Normally defined as being coincident with a spring tide high-water – i.e. Mean High Water Springs (MHWS).

Policy review released for public consultation February 2012.

Describes a coastal foreshore reserve based on a Horizontal Shoreline Datum (HSD) located at the Peak Steady Water Level (PSWL) under storm activity.

Allows for a ‘risk assessment’ based determination of the PSWL.

PSWL = Tide + Surge + Wave Setup

Erosion hazard consideration given to ocean forces and coastal processes that have a 1 in 100 probability of being exceeded in a given year (100-year ARI).

Storm surge inundation consideration given to coastal processes that have a 1 in 500 probability of being exceeded in a given year (500-year ARI).

SLR to 0.9m to 2110, based upon IPCC AR4 (scenario A1F1) and CSIRO 2008.

State Planning Policy 2.6 – States Coastal Planning

Risk of erosion:
- Zones 1 and 2 – Tropical cyclone storm event
- Zones 3 and 4 – Mid-latitude depression or extra-tropical low storm event

Risk of inundation:
- Zones 1, 2 and 3 – Tropical cyclone storm event
- Zone 4 – Mid-latitude depression or extra-tropical low storm event

Policy maintains a default definition of inundation extents:
- “Path of the storm event should be determined to maximise the associated erosion or inundation.”

Buts allows for alternative site specific derivation:
- “Storm events will vary for each location and should be reviewed on a case-by-case basis.”
Study Outline and Objectives

In 2010, Landcorp and the Department of Planning initiated three Coastal Vulnerability Studies for the Pilbara region focused at future growth sites – Port Hedland, Karratha and Onslow.

Each of these sites has been designated as a strategic regional centre in Western Australia.

Cardno was awarded the Port Hedland project.

Cardno recommended that a Monte Carlo cyclone track model be developed to undertake long duration simulation of cyclone tracks and associated storm water levels at Port Hedland.

- This study was the first WA government study to adopt a risk assessment approach to define cyclonic water levels for regional planning.

Project builds on 5 years of continuous investigation and study of coastal processes and hydrodynamics in the Port Hedland region.

Study is focused on shoreline water levels and wave conditions.

Port Hedland Coastal Vulnerability Study

Port Hedland is a strategic regional centre in Western Australia and over the coming 15 years the population is forecast to increase from 19,500 to 40,000.

The Coastal Vulnerability Study assists in identifying development opportunities and constraints for the Port Hedland region to meet the infrastructure requirements as the population doubles over the coming 15 years.

Comprised of four components:
1. Hydrodynamic ocean modelling to assess extreme water levels.
2. Hydrologic assessment of the extreme rainfall conditions.
3. Hydraulic modelling of the combined effects of storm surge inundation and catchment flooding.
Storm Surge Processes

Wind Setup
- Water is driven by wind and ‘piles up’ as it approaches the shore

Barometric Setup
- 1 cm rise in sea level for each hPa below seasonal average (~1005 to 1011 hPa)

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Delft3D Storm Tide Model System

Coupled wind, wave and hydrodynamic model system

Extensive calibration and validation
- 3 years of wave data
- More than 6 separate current and water level validation exercises
- Six selected historical cyclones

Key model aspects:
- Quality of bathymetry data is critical, tide propagation across board, shallow shelf is very sensitive to shallow water wave celerity
- Roughness important within estuary, coastal hydrodynamics not particularly sensitive to roughness
- Wind drag coefficients have to be limited compared to D3D defaults
- Tide, wave and storm surge interactions are HIGHLY NON-LINEAR!
- Domain decomposition generally used - Grid optimisation important, 6 grids - 4 core utilisation

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### Delft3D Storm Tide Model System

**Calibration Procedure**

1. **Wind and Pressure Model**
   - **Inputs:** Measured (BoM) cyclone track and central pressure data
   - **Procedure:** Compare modelled and measured winds and pressure
   - **Objective:** Best fit wind and pressure field

2. **SWAN Wave Model**
   - **Inputs:** Modelled windfield, bathymetry
   - **Procedure:** Compare modelled and measured wave parameters
   - **Adjustments:** Model parameters, particularly friction coefficients
   - **Objective:** Best fit wave field

3. **Delft3D Hydrodynamic Model**
   - **Inputs:** Modelled wind and pressure field, bathymetry, offshore modelled wave conditions, variable bed roughness description
   - **Procedure:** Adjust model parameters, particularly wind drag coefficients
   - **Objective:** Best fit hydrodynamic model

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**Calibrated model system**

For application as ocean inundation model system

- **Adjust wind model parameters:** including RMW and B parameter
  - **Objective:** Improve agreement with measured data
Cardno (2011) presents a model investigation of the influence of the phasing between the tide and the cyclone track.

Simulations undertaken for a synthetic cyclone:
- Central pressure @ landfall = 925 hPa
- Crossing 43km west of Port Hedland
- Track phase shifted relative to the tide +/- 6 hours @ 2-hour intervals

Whilst initially cyclones can be selected from the MC database on intensity or surge potential, a sufficiently large sample needs to be simulated with jointly occurring random tides in a process model.
Spoil Bank Interaction

1939 Cyclone – Photo taken outside Esplanade Hotel showing storm tide estimated at +5.7m AHD, +2m above HAT.

Applying Delft3D to Determine Long Return Period Design Criteria (up to 5000 Years ARI)

A range of study approaches can be adopted:

1. Historical hindcast
   - Relatively high cyclone frequency but extrapolation of design levels limited to about 100 to 200 years ARI
   - Difficult to define jointly occurring water levels, waves and currents

2. Synthetic Track Simulation
   - Can potentially simulate a very large sample synthetic sample set
   - Developing a robust synthetic track database is challenging
   - Computational capacity limits simulations

3. Numerical Simulation
   - Expand a sample set of results from a process based model system using a numerical simulation procedure
   - Computationally efficient
   - Provides a solution to the effect of jointly occurring water levels
   - Non-linear interactions and complexities due to cyclone track neglected
Stochastic Simulation – Monte Carlo Models

A range of approaches exist to determine design cyclonic water levels

1. Analysis of historical data or modelled hindcast data
2. Empirical simulation techniques
3. Historical track translation techniques
4. Stochastic simulation techniques, e.g., Monte Carlo models
5. Global scale atmospheric and oceanographic process modelling

Monte Carlo modelling techniques have been widely applied in cyclone water level and wave studies

- Department of Natural Resources and Mines (2001)
- Widely adopted in Queensland studies:
  - Moreton Bay Region: Cardno Lawson Treloar (2009)

The aim of this project was to develop a Monte Carlo cyclone track model which replicated spatial and temporal variability in cyclone parameters (heading, speed, and central pressure) in a framework that is flexible and can be easily deployed to different sites.

Monte Carlo Model Development

Stochastic modelling requires careful analysis of comprehensive data sets to produce a robust and realistic model

A range of BoM data sets utilised: Best Track, re-analysis and operational

All data re-sampled to 1-hour time step

Analyses undertaken on all cyclones which passed within 500km of Port Hedland post-1960, CP < 980hPa (77 events)

Analysed variables:

- Time of origin (adopted to be the time at which it entered a 1,000km radius from Port Hedland);
- Location of origin;
- Central pressure;
- Forward speed, and
- Cyclone heading.
Model Probability Distributions

- Spatial probability functions developed for rates of change with time for key cyclone variables:
  - Speed: $\frac{dV_{fwd}}{dt}$
  - Heading: $\frac{dH}{dt}$
  - Central pressure: $\frac{dP}{dt}$
- Probability distributions developed for a 250km Cartesian grid
- For grid cells with an even split between over-water and over-land area separate distributions were developed

Model Operation

1. Simulations initiated 1000km from Port Hedland and proscribed:
   - Location of origin
   - Central pressure
   - Forward speed
   - Cyclone heading
2. Cyclones simulated as a generalised random walk:
   \[ Y = Y_0 + \sum_{i=1}^{n} \Delta V_i \]
3. Model applies conditional probability – change in parameter variable dependent on value at previous time step:
   \[ P(Y = y \mid X = x) = \frac{P(X = x \land Y = y)}{P(X = x)} \]
Model Verification

Comparison central pressure – historical and 200 Monte Carlo simulations (50-years each)
Complete model database comprises 16,000 events.

An appropriate sub-sample of severe events must be selected for detailed simulation in the process model system.

A multi-tiered ranking algorithm applied to identify severe cyclones which could generate extreme water levels.

In Cardno (2011), an empirical non-linear regression model for storm surge generated from a 35 sample of hindcast events using the calibrated process model system.

Limitation is that this algorithm neglects the interaction between tide and the total residual water level.
Regional Ranking Model

Top 1000 events identified by Regression Model implemented in coarse regional scale coupled wind-hydrodynamic-wave model
Grid resolution from 1500m x 1500m to 500m x 500m at site
5 min time step sufficient to account for physical process at coarse resolution
Regional model predicts 90% of variability present in Full Process model for hindcast events with no bias

Design Event Selection

EVA applied to regional ranking results and design events selected

ARI 100 event, low intensity but occurred at large spring tide

<table>
<thead>
<tr>
<th>Cyclone Event (ARI)</th>
<th>Minimum Central Pressure (hPa)</th>
<th>Minimum Distance to Port Hedland (km)</th>
<th>Central Pressure at Minimum Distance (hPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>100</td>
<td>958.1</td>
<td>86.7</td>
<td>962.2</td>
</tr>
<tr>
<td>200</td>
<td>914.1</td>
<td>70.3</td>
<td>915.0</td>
</tr>
<tr>
<td>500</td>
<td>921.7</td>
<td>43.3</td>
<td>928.5</td>
</tr>
</tbody>
</table>
Combined Ocean and Catchment Flooding

The Port Hedland CVS also involved a comprehensive catchment flood assessment for the Port Hedland region.

Analysis of historical data indicated that there was no significant correlation being cyclonic ocean water levels and rainfall.

Cardno worked with the Department of Transport and Department of Water to formulate a conservative model to account for Joint Occurrence of ocean and catchment flooding:

- 1:5 ARI allowance up to 100-years ARI, i.e. 100-year ARI ocean level coincident with 20-year catchment flows (and vice versa).
- 1:10 ARI allowance beyond 100-years ARI, i.e. 500-year ARI ocean level coincident with 50-year catchment flows (and vice versa).

Design Levels

<table>
<thead>
<tr>
<th>ARI (years)</th>
<th>Design Peak Total Still Water Level (mAHD)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>East Port Hedland</td>
</tr>
<tr>
<td>2</td>
<td>4.4</td>
</tr>
<tr>
<td>10</td>
<td>4.9</td>
</tr>
<tr>
<td>20</td>
<td>5.0</td>
</tr>
<tr>
<td>50</td>
<td>5.3</td>
</tr>
<tr>
<td>100</td>
<td>5.9</td>
</tr>
<tr>
<td>200</td>
<td>6.0</td>
</tr>
<tr>
<td>500</td>
<td>6.6</td>
</tr>
</tbody>
</table>
Conclusions

Monte Carlo cyclone track model is an accepted technique to simulate physically complex cyclone track generation and propagation processes

A Monte Carlo model system has been developed for the Pilbara region which replicates spatial and temporal variations in historical cyclone tracks and intensity

The model system has been demonstrated in a regional inundation risk assessment study which required the determination of long return period design water levels

The architecture of the model system means it is highly adaptable and can be readily deployed to other locations

Careful selection of the model domain and grid discretisation is required to account for variations in cyclone processes and available data sets

Current and Further Model Developments

A regional scale process model has been developed to allow a large number of cyclones (>3,000 events) to be simulated in the hydrodynamic model (including tide) within a short time period (<5-days, 20 CPU's)

Open source software and cloud computing enable a large number of events to be simulated with coupled wind, waves and hydrodynamics in high resolution

Implementation of a physically based condition to limit the potential minimum central pressure

Integration of larger scale atmospheric forcing into the model to allow complex wind fields to be generated for each Monte Carlo model event
Thank you and Questions

 ENGINEERS AUSTRALIA - NSW COASTAL, OCEAN AND PORT ENGINEERING PANEL