Components of Storm-induced Water Level along the Coastal Margin and Related Effects on the Nearshore Wave Environment

Hans R. Moritz and Heidi P. Moritz

U.S. Army Corps of Engineers, Portland District
Portland, Oregon USA
OUTLINE

Review Water Level Components – as Affected by Storm Wave Action

Examine Observed Infragravity Transients – Produced by Shoaling Bound Waves

Examine Consequences of Infragravity Transients – Effects on Coastal Margin Use

Consider Hypothesis: Storm Surge Enhanced by Infragravity Transients
Conclusions

The storm water level that acts upon the coastal margin is a product of many components (processes).

A basic understanding of these components should be attained before initiating significant coastal zone planning or implementing the design and construction of coastal infrastructure, at a given location.

Hypothesis: $\Delta \eta$ may be responsible for a considerable fraction of the storm surge which affects coastal margins.

Based on an initial assessment, this “$\Delta \eta$-Surge” warrants further evaluation.

Infragravity Transients ($\Delta \eta$) of 1-2 meters and associated rip currents elevate the RISKS to life and property within the active coastal margin.

More work is needed to fully parameterize the estimation of $\Delta \eta$ and use this information to reduce risk along the coastal zone.
3 MAR 1999 - Extr Trop Low
image courtesy of NOAA

29 AUG 2005 - Hurricane
image courtesy of NOAA
Water Level and Waves Offshore SW Pass, LA: 26-31 Aug 2005

Waves, 60 mi. offshore

Wave Height, m, Hsig

Days after 26 AUG 2005
Water Level and Waves Offshore SW Pass, LA: 26-31 Aug 2005

The continental shelf break is 30 km offshore.

- Storm Surge, max=5.8 ft
- Wave Height, m, $H_{sig}$
Water Level and Waves Offshore Mouth of Columbia River, OR / WA: 3 Mar 1999

Waves, 18 mi. offshore

Days after 1 MAR 1999

Wave Height, m

Wave Height, m, Hsig
Water Level and Waves Offshore Mouth of Columbia River, OR / WA: 3 Mar 1999

- Storm Surge, max=5.2 ft
- Wave Height, m, Hsig

Continental shelf break is 30 km offshore

Days after 1 MAR 1999

Surge (above Predicted Tide), ft
Wave Height, m

Days after 1 MAR 1999

1 1.5 2 2.5 3 3.5 4
"Open" Coast Storm Surge Comparison
Hurricane (GOM) vs. Extr. Low (PacNW)

Potential Surge Limit?

FOR STEEP “Open” COASTAL MARGINS
Cross-Shore Profile: 5 km South of Columbia River Mouth

- 13 m
- 35 m

Elevation (ft, MLLW)

Distance Offshore, west, miles

Nov98 – Mar99

Sep-Dec03

5 km S of MCR
Hmo = 11.5 m, Tp = 17 sec

WSE, m

IG - WSE, m

IG-Current: U: Onshore - Offshore

IG-Current: V - Alongshore

Onshore

Offshore

North

South

WSE - Infragravity
Hmo = 5 m, Tp = 17 sec
Longwave (IG, $\eta$) Propagation in Nearshore and Shoreface

- Black line: still water level (non-storm perturbed)
- Blue line: short waves (sea/swell)
- Red line: long (bound) waves - water level transients, $\eta$
Longwave Propagation, Nearshore, based on Solitary Wave behavior

Depth-limited Translation speed = $\sqrt{g \times (\text{depth} + \text{wave height})}$

Excursion = 10s - 100 meters
Persist for 1-2 minutes

Departure point
Δη = 1 m
Bore moving upslope - Decelerating

Beach Slope = 1 vert : 70 horz.

Wave (Bore) Speed at “0” Still Water level – Departure point

Translation speed = $\sqrt{g \times (\text{longwave height}, \Delta \eta)}$

= 3 m/sec........ for Δη = 1 m
Along the Pacific NW coast of the US, several people each year succumb to “sneaker waves”....... 

Appear to be associated with transient water levels ($\Delta \eta$) produced by groups of large waves.

Landward Speed = 2-4 m/sec

Bore height = 0.3 – 1.5 m

Duration = 1-2 minutes

Excursion Distance = 10-100 meters

Return Flow more dangerous than run-up
Storm water level = \text{WSE due to tides} + \text{storm surge} + \text{infragravity transients (waves)}

Tidal WSE results are presented in terms of an annualized percent exceedance for Astoria 1987-2007, applied to MCR using a 0.87 modulation factor. The hourly high tide level exceeded 10% of the time during a given year = 3.4 ft NGVD (6.9 ft MLLW). The 1% annual high tide is 4.6 ft NGVD (8.1 ft MLLW).
Components of Coastal Margin Water Surface Elevation at MCR

Storm water level = WSE due to tides + storm surge + infragravity transients (waves)

Tidal WSE results are presented in terms of an annualized percent excedance for Astoria 1987-2007, applied to MCR using a 0.87 modulation factor. The hourly high tide level exceeded 10% of the time during a given year = 3.4 ft NGVD (6.9 ft MLLW). The 1% annual high tide is 4.6 ft NGVD (8.1 ft NGVD).

Storm surge results are based on a partial-duration frequency analysis for a 20-yr period of record using data that was recorded at Toke Pt, WA (1-hr interval). Results were extrapolated to a 100-yr frequency of occurrence and are presented here in terms of a cumulative distribution. The 10-year (0.9) storm surge = 4.7 ft.
Components of Coastal Margin Water Surface Elevation at MCR

Storm water level = WSE due to tides + storm surge + infragravity transients (waves)

Tidal WSE results are presented in terms of an annualized percent exceedance for Astoria 1987-2007, applied to MCR using a 0.87 modulation factor. The hourly high tide level exceeded 10% of the time during a given year = 3.4 ft NGVD (6.9 ft MLLW). The 1% annual high tide is 4.6 ft NGVD (8.1 ft).

Storm surge results are based on a partial-duration frequency analysis for a 20-yr period of record using data that was recorded at Toke Pt, WA (1-hr interval). Results were extrapolated to a 100-yr frequency of occurrence and are presented here in terms of a cumulative distribution. The 10-year (0.9) storm surge = 4.7 ft.

Infragravity transient results are based on an estimated cumulative distribution. The 10-year (0.9) estimate for 50 ft water depth is = 5 ft.

2-yr Storm water level, inshore of 50 ft depth = 3.4 + 4 + 4.5 = 11.9 ft NGVD

Why is there a lack of variation in storm surge and IG Transient?
Results are based on a partial-duration frequency analysis for a 17-yr period of record using data that was recorded at 1-hour intervals. Results were extrapolated to a 100-yr frequency of occurrence using a fitted Wiebel distribution and are presented here in terms of a cumulative distribution. The 10-year wave = 37.5 ft

The annual storm wave condition is large, producing nearshore IG energy near max value.
Modulation of Water Surface Elevation ($\Delta \eta$, O-min)
–Can temporarily increase nearshore water depth

Allowing Larger Waves to attack infrastructure

Columbia River Bar Pilots Photo
Effect of Transient Water Level, $\Delta \eta$, when Wave Height ($H$) is depth-limited

$\Delta \eta$ has taken the role of $\Delta H$ in the following performance functions

<table>
<thead>
<tr>
<th>Type of Loading Condition or Hazard Scenario Affected by a Transient Water Level ($\Delta \eta$)</th>
<th>Performance Function for Coastal Infrastructure Loading Increase or Coastal Zone Hazard</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Conventional Structures (rigid)</strong></td>
<td></td>
</tr>
<tr>
<td>-- Static Loading (hydrostatic)</td>
<td>$\left(\Delta \eta\right)^2$</td>
</tr>
<tr>
<td>-- Dynamic Loading (wave action)</td>
<td>$\left(\Delta \eta\right)^2$</td>
</tr>
<tr>
<td>-- Overtopping/Interior Protection (waves)</td>
<td>$\left(\Delta \eta\right)^{1.5} \times \exp\left(\text{crest elevation} - (\text{TWSE} + \Delta \eta)\right)$</td>
</tr>
<tr>
<td><strong>Compliant Structures (rubblemound)</strong></td>
<td></td>
</tr>
<tr>
<td>-- Direct Wave Action (armor unit stability)</td>
<td>$\left(\Delta \eta\right)^3$</td>
</tr>
<tr>
<td>-- Lee-side Wave Action (armor unit stability)</td>
<td>$\left(\Delta \eta\right)^3 \times \exp\left(\text{crest elevation} - (\text{TWSE} + \Delta \eta)\right)$</td>
</tr>
<tr>
<td><strong>Nearshore and Structure Foundation Stability</strong></td>
<td></td>
</tr>
<tr>
<td>-- Sediment Transport Potential (seabed erosion)</td>
<td>$\left(\Delta u\right)^{2.x} + \left(\Delta \eta\right)^{1.x}$</td>
</tr>
<tr>
<td><strong>Wave Run – Up on Shoreface</strong></td>
<td></td>
</tr>
<tr>
<td>-- Run-up Distance</td>
<td>$2 \Delta \eta \times \text{beach slope}$</td>
</tr>
<tr>
<td>-- Run-up Speed</td>
<td>$\left(2 \Delta \eta\right)^{1/2}$</td>
</tr>
<tr>
<td>-- Run-up Depth (water depth increase before $\Delta \eta$)</td>
<td>$2 \Delta \eta$</td>
</tr>
</tbody>
</table>
Sneaker Wave Action: IG Transient, $\Delta \eta$, producing enhanced run-up and erosion
Infragravity Energy -> Super Swash

High Tide Elevation
Transient Water Level at the Shoreface

Normal Condition

Storm Condition

31 JAN 2006

Erosion of Dune

MHHW + nominal wave run-up
Infragravity Bore produced a 0.5 m Water Level Transient, $\Delta \eta$
Jetty Root Erosion produced by wave Overtopping

Made possible by a transient increase in water level
Result of Dune being Overtopped by at least 1 meter over dune crest

+ 8.5 m MLLW = Overtopping El.

Top of Dune ≈ +7.6 m MLLW

Static Storm Surge Water Level = +4.3 m MLLW
Breach Established by Elevated (transient) Water Level

Allowing increased Wave Action to Attack Jetty Root
Levee being overtopped by short waves propagating on top of storm surge during Hurricane Katrina landfall. The degree of overtopping is considerable.

Under such conditions, infrastructure behind the level can be damaged or incapacitated.

This level of overtopping can lead to catastrophic failure of coastal flood protection.
Hypothesis:
Storm Surge Is Affected by Infragravity Transients ($\Delta \eta$)

A component of storm surge evolves as a series of landward propagating longwaves ($\Delta \eta$), which introduce water and momentum into the nearshore.

Each successive longwave transient ($\Delta \eta$) is superimposing additional water/momentum on the previous surge transient.

As the water level increases, depth limited storm waves ride on top of the long waves to add destructive power to the storm surge event.

If an efficient path (conveyance) for return flow can not be established, the water level (surge) will increase unit conveyance is established such that added shoreward momentum (vol flux) = return flow

Verify: 1) By Review of Surge Event Photography. 2) Apply Bouss-2D Model, forced by Infragravity BC
Arrival of Hurricane Katrina storm surge, as it came over US Hwy 90 at Gulfport, MS approximately two hours before storm peak made landfall.

Surge propagating landward in terms of individual bores, long wave transients ($\Delta \eta$), with shortwaves traveling on top.
The surge arrived at the hotel location in terms of long wave pulses, with short waves traveling on top of the long wave transients ($\Delta \eta$).

The level of the water outside of the hotel is 2-3 ft higher than inside the hotel due to surge transients, $\Delta \eta$.

An eyewitness account: “I suddenly envisioned what a tsunami must look like, and realized that I was in a situation similar to that. I watched as the waves were coming in from the Gulf of Mexico.

They were very long, two-to-three foot tall waves that didn’t crash, but just moved in--the classic storm surge”.

Eyewitness testimony and photography provided by Mike Theiss – UltimateChase.com
Before and during a storm surge event at Port Hedland, Australia, 1939

Photo courtesy of Australia Bureau of Meteorology
BOUSS-2D Patch Test

BOUSS-2D is a comprehensive numerical model based on time-domain solution of Boussinesq-type equations.

The fully non-linear equations are solved through the surf zone to allow evaluation of wave shoaling-diffraction-bottom friction-breaking, wave-wave interaction, and generation-dissipation of IG motion.

The model was applied using a nearshore domain for an area 5 km south of MCR.

The model domain covered an area of 14 km (onshore-offshore) x 8 km (alongshore).

Water depth within the model domain varied between -38 m (below NGVD) at the offshore boundary to 6 m (above NGVD) at the shore. The domain was discretized using 20x20 m cells.

The storm wave-field simulated within the domain was generated using a irregular multi-directional bi-modal spectrum (Ochi-Hubble, Tp1 = 160 sec, Hs1=2 m, nn1=2, Tp2 = 17 sec, Hs1=12.3 m, nn2=3).

Tp1 was implemented based on the observations of long wave energy at MCR in water depth 35 m.

The model was run for 3,000 s using a 0.4 sec time step. Output was obtained during t=2,000-3,000 sec.
Boussinesq Estimate for Water Surface Elevation Time Series
Based on Offshore Bi-Modal Wave Spectrum (Hsig = 12.5 m, Tp1 = 160 sec, Tp2 = 17 sec)

Time, sec

WSE, NGVD, meters
Boussinesq Estimate for Water Surface Elevation Time Series
Based on Offshore Bi-Modal Wave Spectrum (Hsig = 12.5 m, Tp1 = 160 sec, Tp2 = 17 sec)
Boussinesq Estimate for Time-Averaged Water Surface Elevation
Based on Offshore Bi-Modal Wave Spectrum (Hsig = 12.5 m, Tp1 = 160 sec, Tp2 = 17 sec)
Boussinesq Estimate for Time-Averaged Water Surface Elevation
Based on Offshore Bi-Modal Wave Spectrum (Hsig = 12.5 m, Tp1 = 160 sec, Tp2 = 17 sec)

Distance Offshore, m

WSE, m, NGVD

Seabed/10, m, NGVD

Seabed Elevation, m
Bouss-2D Average WSE
Conclusions

The storm water level affecting “open” coastal margins can be composed of many processes (components).

Infragravity (IG) Transients, forced by groups of storm waves, may have a significant effect on the coastal margin.

IG Transients ($\Delta \eta$) of 1-2 meters and associated rip currents elevate the RISK to life and property within the active coastal margin.

More work is needed by the wave science/engineering community to fully parameterize the estimation of transient water level behavior, and use this information to improve our utilization of the coastal zone.

Hypothesis: $\Delta \eta$ may be responsible for a considerable fraction of the storm surge which affects coastal margins.

The wave science/engineering community should consider further evaluation of this potentially important storm surge process.