NONLINEAR PROPAGATION OF STORM WAVES: INFRAGRAVITY WAVE GENERATION AND DYNAMICS

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PRESENTATION OUTLINE

I. Motivation

II. Nonlinear Wave Propagation in the Nearshore

III. A Numerical and Experimental Study on Infragravity Waves

IV. Chile as an International Natural Coastal Laboratory
1. MOTIVATION

- The number of ND have skyrocketed over the last century
- The number of affected people and estimated damage follow the trend
- The number of dead people decouples from the trend

Source: EM-DAT International Disasters Database
I. MOTIVATION

• Extreme, large and rapid flooding
  – Tsunamis, flash floods, GLOF, storm waves

• Significant consequences
  – Human lives
  – Facilities and structures
  – Social and environmental impact
I. MOTIVATION

Recent Large River Floods in Chile

BíoBío, 2006
Talca, 2008
Licantén, 2008
Chaitén, 2008
Mapocho, 1982
BíoBío, 2006
Recent Glacial Lake Outburst Floods in Chile

- GLOF in the Chilean Patagonia (Chachet 2)
- More than 6 episodes since April 2008
- 4.5m stage rise and 3500m3/s peak discharge in Baker River in less than 48 hours.
I. MOTIVATION

Recent Major Tsunamis in Chile

Valdivia, 1960

Constitución, 2010

Pelluhue, 2010
Recent Major Storm Waves in Chile

Nonlinear waves are in permanent action, shaping our environment, and questioning the way the society fits in it

- Wide temporal and spatial scales
- Complex nonlinear interactions
- Strange consequences?

⇒ Amazing research opportunities for contributing to the understanding of these processes and their consequences

Truc vert beach, French Atlantic Coast
Courtesy of P. Larroudé (LEGI)
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II. NONLINEAR WAVE PROPAGATION

Shoaling, breaking and run-up of an incident laboratory wave

⇒ “Simplified” 2DV view of nearshore wave propagation

Source: Laboratory Experiment in the LEGI Wave Flume, France
II. NONLINEAR WAVE PROPAGATION

Long wave (shallow water) models

\[ \sigma \leq 0.1 \]
II. NONLINEAR WAVE PROPAGATION

Wave merging in the inner surf zone
*Sénéchal, Dupuis, Bonneton (2001)*

![Graphs showing wave merging in the inner surf zone](image)

Higher harmonics release after a bar
*Sénéchal, Bonneton, Dupuis (2002)*

![Graphs showing higher harmonics release](image)
Regular waves shoaling over a submerged bar, and higher harmonics release once water depth increases

⇒ Generation of bound higher harmonics in the shoal (shallow water propagation)
⇒ Over “intermediate” depths, higher harmonics travel at their “own” speed

Source: Cienfuegos et al., 2007; Dingemans, 1994 experiments
Wave propagation creates a set-down and set-up in the mean sea level
Fission of the main wave front for longer period waves

Source: Cienfuegos et al., 2010; Hansen and Svendsen, 1979 experiments
Tsunami wave fission in the Sendai area, Japan 2011
Set-down/Set-up over a uniform beach under regular wave propagation

⇒ Radiation stress concept for wave-averaged quantities (Longuet-Higgins and Stewart, 1962)

\[
\frac{\partial S_{xx}}{\partial x} + \rho g (\bar{\eta} + h) \frac{\partial \bar{\eta}}{\partial x} = 0
\]

\[
S_{xx} = E \left\{ \left[ \cos^2 \theta + 1 \right] \frac{C_g}{C} - \frac{1}{2} \right\}
\]

Source: Bowen et al., 1968
II. NONLINEAR WAVE PROPAGATION

Infragravity wave (IG) generation under random wave forcing
⇒ Long waves forced by high-frequency wave groups

2nd Order Long Wave Generation Mechanism

Negative correlation between group envelope and IG waves

Mean water level pulsation associated to wave groups’ set-up/set-down (Longuet-Higgins and Stewart, 1962)
⇒ Bound long waves propagating at group velocity
II. NONLINEAR WAVE PROPAGATION

Infragravity wave (IG) generation under random wave forcing

⇒ Long waves forced by a variable breakpoint location

The slow modulation of the breaking point under a random wave field produces a dynamic set-up/set-down

Adapted from L.H. Holthuijsen, 2007

Positive correlation between group envelope and IG waves

SURF BEAT (Symonds, 1982)
II. NONLINEAR WAVE PROPAGATION

Practical consequences of IG waves: Increased run-ups

⇒ Random short waves transfer energy to infragravity waves while propagating towards the shore

⇒ Very important for swash zone dynamics and maximum observed run-ups
Practical consequences of IG waves: Edge waves

Trapped Edge Waves at Truc Vert Beach, France

- The breaking process is responsible for the release of IG waves
- IG waves reflect at the coast (swash)
- Refraction traps IG (so-called edge waves)
Practical consequences of IG waves: Edge waves

Incident periodic waves: 
H=1m ; T=100s ; θ₀=30°

Uniform beach profile: 
h₀=10 ; s=1/40

⇒ Reflected waves are trapped and propagate in the alongshore direction

⇒ Important consequences for maximum run-up distribution

NSWE FV model developed by M. Guerra (PUC MSc thesis)
Numerical simulation by José Galaz (PUC undergrad student)
II. NONLINEAR WAVE PROPAGATION

Practical consequences of IG waves? Rip instabilities

- Frontal incident random wave trains with a small amplitude perturbation in the center
- Rip current generation
- Slow mean current pulsations
- Quasi-periodic ejection of drifters

PhD thesis of Leandro Suarez (PUC-LEGI grad student)
Suarez et al., ICCE 2012; Suarez et al., CD 2013
Pan-American Advanced Studies Institute
The Science of Predicting and Understanding Tsunamis, Storm Surges and Tidal Phenomena
Boston University – Mechanical Engineering

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Different methods to cope & understand water waves

- Laboratory experiments
  - MODLIT project

- Field measurements
  - ECORS project

- Modeling

- DNS and LES
  - IDAC program

- Nearshore modeling
  - MODLIT and IDAC

Source: P. Bonneton, 2010
General Definitions and Framework

Arbitrary bottom bathymetry

Incompressible and inviscid fluid

Quasi-Irrotational flow

\( L \)

\( h \)

\( a \)

\( h_0 \)
Non-dimensional depth-averaged mass and momentum equations

\[ h_t + \varepsilon [h \bar{u}]_x = 0 \]

\[ \varepsilon [h \bar{u}]_t + \left[ h \left( \varepsilon u^2 + \bar{p} \right) \right]_x + \xi_x p|_\xi = 0 \]

Where the pressure field is written as:

\[ p(x, z, t) = (\varepsilon \eta - z) + \varepsilon \sigma^2 \int_{z}^{\varepsilon \eta} \Gamma(x, z, t) dz \]

and the function \( \Gamma \) represents the vertical acceleration of fluid particles:

\[ \Gamma(x, z, t) = \frac{Dw}{Dt} = w_t + \varepsilon \left( uw_x + \frac{1}{\sigma^2} w w_z \right) \]
III. INFRA GRAVITY WAVES

Using approximate expressions for the velocity field (potential flow theory) we get the fully nonlinear weakly dispersive Serre/Green-Naghdi Equations (Cienfuegos et al., 2006; Lannes and Bonneton, 2009)

\[ h_t + \varepsilon [hu]_x = 0 \]

\[ (hu)_t + \varepsilon (hu^2)_x + h(h + \xi)_x + \sigma^2 \left\{ h^2 \left( \frac{1}{3} P(x,t) + \frac{1}{2} Q(x,t) \right) \right\}_x + \]

\[ + \sigma^2 \xi_x h \left( \frac{1}{2} P(x,t) + Q(x,t) \right) = O(\sigma^4) \]

Where:

\[ P(x,t) = -h(u_{xt} + \varepsilon uu_{xx} - \varepsilon u_x^2) \quad \text{Dropping overbars for simplicity} \]

\[ Q(x,t) = \xi_x (u_t + \varepsilon uu_x) + \varepsilon \xi_{xx} u^2 \]
A 4th Order FV S/G-N Model (Cienfuegos et al., 2006, 2007)

- A strongly nonlinear and weakly dispersive Boussinesq system $O(\sigma^4)$

\[
\begin{align*}
    h_t + F_x &= 0 \\
    q_t + G_x &= 0
\end{align*}
\]

With the following definitions for flux functions and auxiliary variables:

\[ F = h u \]

\[ G = u q + g (h + \xi) - \frac{1}{2} u^2 (1 + \xi_x^2) + h u_x \xi_x u - \frac{1}{2} (hu_x)^2 \]

\[ q = (1 + r)u - \frac{1}{3h} \left( h^3 u_x \right)_x \]

\[ r = (h_x + \xi_x)\xi_x + \frac{1}{2} h \xi_{xx} \]
Incorporating Breaking Energy Dissipation (Mignot and Cienfuegos, 2009; Cienfuegos et al., 2010)

- Diffusive-like terms in both, mass and momentum conservation equations

\[
\begin{align*}
    h_t + F_x + D_h &= 0 \\
    q_t + G_x + \frac{1}{h} D_{hu} &= 0
\end{align*}
\]

\[
D_h = \left( v_h h_x \right)_x
\]

\[
D_{hu} = \left[ v_{hu} (hu)_x \right]_x
\]

Local re-distribution of mass and momentum below breakers

Similar to Kennedy et al., 2000
• Typical wind-generated waves: 0.05Hz (20s) – 1Hz (1s)

• Nonlinear processes (shoaling, breaking, swash) generate infragravity (IG) waves: 0.001Hz (1000s) – 0.05Hz (20s)
Experimental Investigation at the Instituto Nacional de Hidráulica

- 70m long x 1.5m wide x 1.5m deep wave tank
- Piston wave paddle with active absorption (DHI)
- Resistive probes for free surface measurements
- Sontek MicroADV for velocity measurements
- Very mild slope beach 1/80
Random Incident Wave Field

• Jonswap spectrum (Hasselmann, 1973) for incident wave field

\[ T_p = 4 \text{ s (0.25Hz)} \; ; \; H_{mo} = 18 \text{ cm} \; ; \; h_0 = 52\text{cm} \]

• Without phase structure (uniform random distribution \([0,2\pi]\))

• Highly nonlinear shallow water regime

⇒ Although the forcing wave field does not contain energy in the infragravity band, experiments show important energy content at these frequencies
Separation of Incident and Reflected Waves

- Radon transform (Deans, 1983) in time domain to separate incident and reflected signals (Almar et al., 2013)
Model Performance on High Frequency Waves

Wave height and energy distribution

Crest-trough wave asymmetry (Sk)

Left-right wave symmetry (As)

Total

1\textsuperscript{st} harmonic

2\textsuperscript{nd} harmonic
III. INFRAGRAVITY WAVES

Spectral Energy Evolution Along the Experimental Flume

Partial reflection at the wave paddle produces low frequency selection in the flume

Natural modes
\[ f_1 = 0.013 \text{Hz} \]
\[ f_2 = 0.023 \text{Hz} \]
\[ f_3 = 0.031 \text{Hz} \]
III. INFRAGRAVITY WAVES

Model Performance in Spectral Energy Evolution

⇒ The model succeeds in transferring energy to higher harmonics and IG waves but no clear modal selection (open boundary condition)
Cross-correlation maps between group amplitude and IG wave amplitude at each location

- Experimental
- Numerical
III. INFRAGRAVITY WAVES

Cross-correlation maps between group amplitude at the first gauge and IG wave amplitude at each location

- Experimental
- Numerical
• A bound IG appears rapidly in the shoaling zone forced by short wave groups (negative correlation slightly lagging the group)

• A positive long wave surge preceding the group develops as the short waves propagate towards the shore (positive correlation running ahead of the group)

• There is a phase shift for the positively correlated IG wave in the inner surf zone

• Both IG waves appear to be partially reflected on run-up (some dissipation by breaking might occur)
III. INFRAGRAVITY WAVES

• The shallow water regime (Cg~C) produces a nearly resonant condition for IG wave forcing (Nielsen and Baldock, 2010)

⇒ The so-called N-shaped long wave is forced as a bound wave in the shoaling zone

Non-resonant condition

Resonant condition

Fig. 1. Steady, bowl-shaped long wave (solid line) driven by a steady, non-resonant wave group (thin line) with \( S_o \) varying as indicated by \(-\times-\).

Fig. 3. At resonance, \( c_g = \sqrt{gh} \), which happens in the shallow water limit, the Gaussian shaped \( S_o \) forcing \(-\times-\) from the wave pulse generates an \( \Pi \)-shaped long wave which grows linearly with time.
III. INFRA GRAVITY WAVES

• The phase shift in the positively correlated IG wave in the inner surf zone is due to a strong interaction between short waves and IG motions in very shallow waters (merging of short frequency waves)

Free surface time series at different locations along the numerical wave flume

Merging of high frequency waves on a bi-chromatic experiment (Van Dongeren et al., 2007)
III. INFRAGRAVITY WAVES

Model Performance for Incident and Reflected IG Waves

- **Total**
  - **Long Wave Time Stacks**
  - **Long Wave Amplitude**
  - **Comment**: Under estimation of incident IG wave

- **Incident**
  - **Long Wave Time Stacks**
  - **Long Wave Amplitude**
  - **Comment**: Good representation of incident IG wave generation and shoaling

- **Reflected**
  - **Long Wave Time Stacks**
  - **Long Wave Amplitude**
  - **Comment**: Under estimation of reflected IG wave

- **Legend**:
  - Black: Experiments
  - Red: Model
  - Dashed line: theoretical free long wave amplitude shoaling
Summary

• Maximum run-ups under highly nonlinear waves are strongly dependent on infragravity wave motions (strong under estimation of maximum run-ups using linear wave theories)

• Fully nonlinear Boussinesq-type equations including breaking and run-up are able to cope with the complex energy transfer processes within the nearshore producing accurate estimations of short wave propagation and IG generation and dynamics

• More research is needed to (fully) understand nearshore wave processes and its (un)expected consequences on morphodynamics and coastal hazards
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Mataquito River Mouth in the Maule Region

Main Wave direction (Deep water)
Sediment Transport

Source: Google earth & Geo eye
This area was heavily affected by the 2010 Tsunami

- The land subsided (~0.5-1.0m)
- The sand spit was washed away by tsunami waves
- The sand spit rapidly reformed under highly energetic waves (strong wave and aeolian alongshore sand transport)
- Three years of low river discharge

⇒ The sand spits reformed but different than before
IV. Natural Coastal Laboratory
IV. Natural Coastal Laboratory

PASI Coastal Hazards 2013
Boston University – Mechanical Engineering
UTFSM 2-13 January 2013
IV. Natural Coastal Laboratory

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