Pan-American Advanced Studies Institute
The Science of Predicting and Understanding Tsunamis, Storm Surges and Tidal Phenomena

Boston University – Mechanical Engineering

NONLINEAR PROPAGATION OF STORM WAVES: INFRAGRAVITY WAVE GENERATION AND DYNAMICS

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Associated National Universities

PRESENTATION OUTLINE

I. Motivation

II. Nonlinear Wave Propagation in the Nearshore

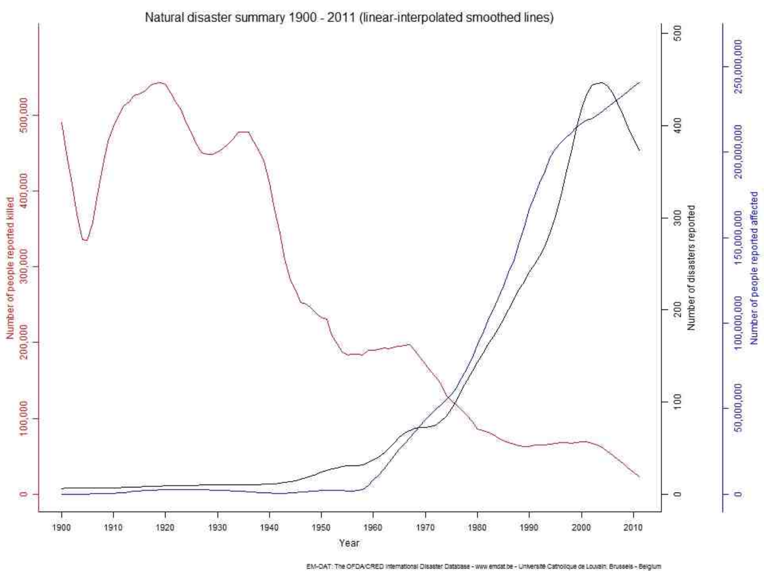
III. A Numerical and Experimental Study on Infragravity Waves

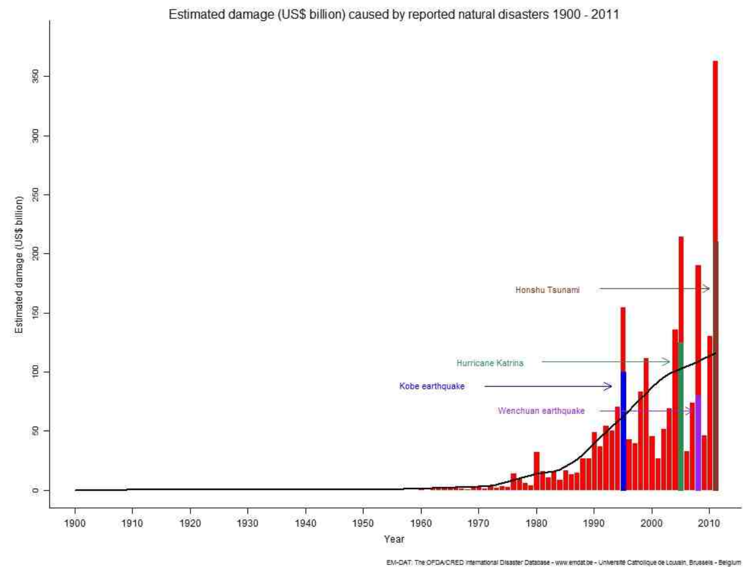
IV. Chile as an International Natural Coastal Laboratory

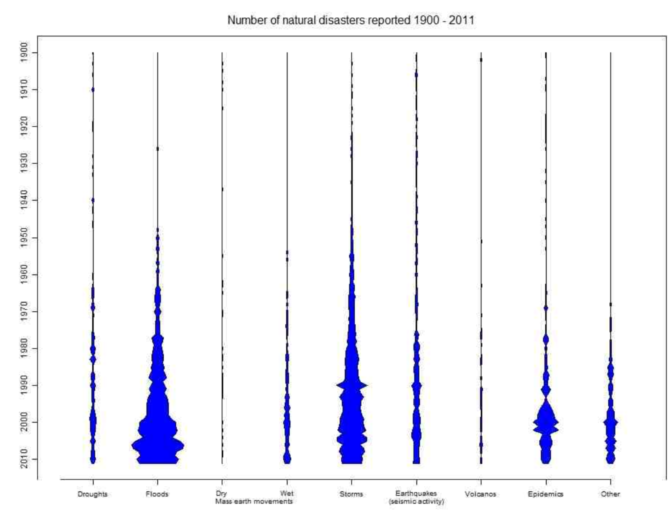
I. MOTIVATION

PASI Coastal Hazards 2013
Boston University – Mechanical Engineering

UTFSM 2-13 January 2013







- **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
CRED - http://www.emdat.be/

I. MOTIVATION

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

- **Significant consequences**
  – Human lives
  – Facilities and structures
  – Social and environmental impact



Recent Large River Floods in Chile

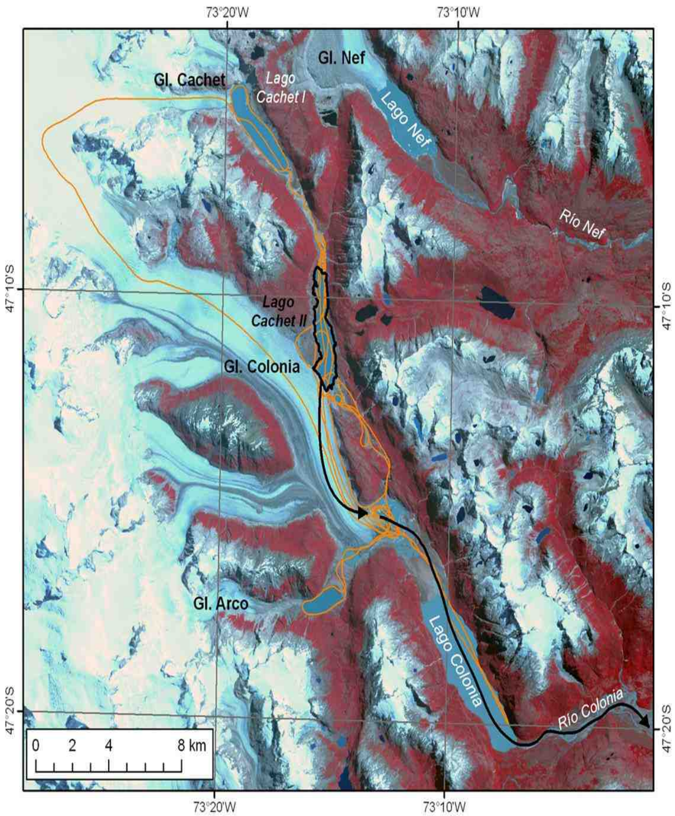

Talca, 2008


Chaitén, 2008


BíoBío, 2006


Licantén, 2008


Mapocho, 1982



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.

Glaciologia.cl

Recent Major Tsunamis in Chile


Valdivia, 1960


Constitución, 2010


Pelluhue, 2010

Recent Major Storm Waves in Chile

Source : El Mostrador – http://www.elmostrador.cl/
August 16th 2012

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

Truc vert beach, French Atlantic Coast
Courtesy of P. Larroudé (LEGI)

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

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

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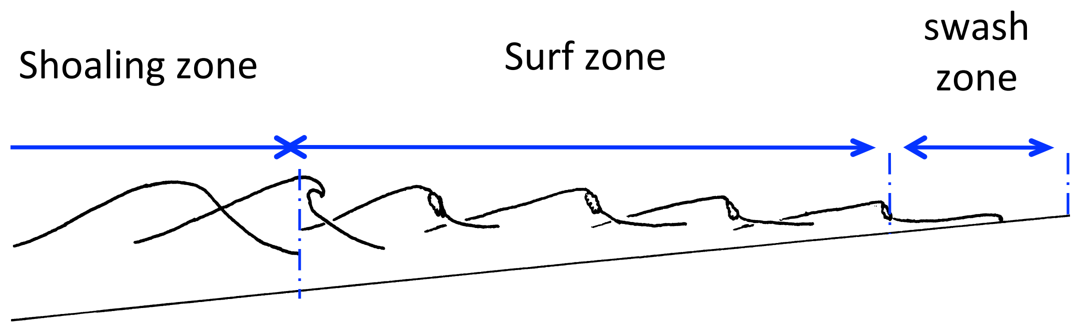
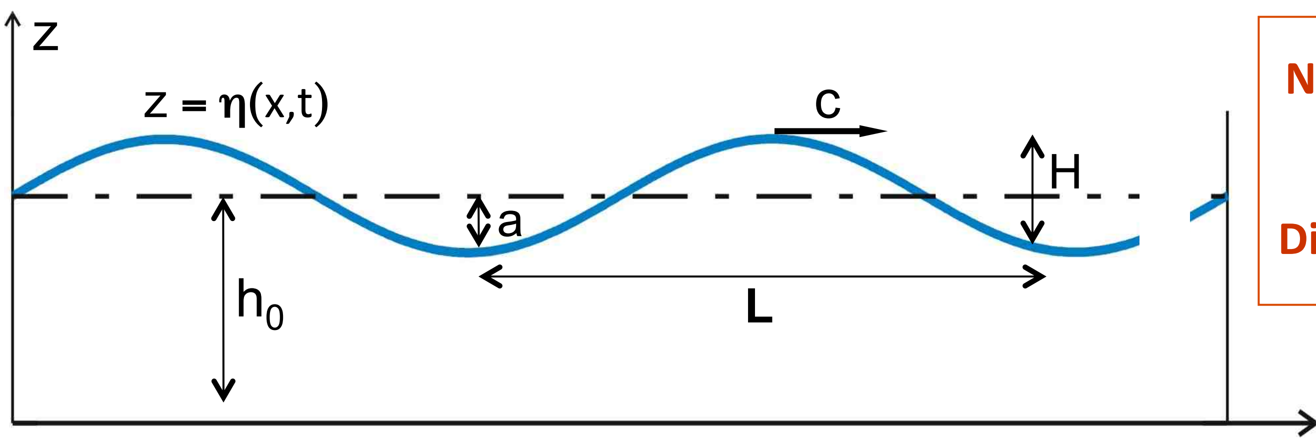
Shoaling, breaking and run-up of an incident laboratory wave

Source : Laboratory Experiment in the LEGI Wave Flume, France

⇒ "Simplified" 2DV view of nearshore wave propagation

II. NONLINEAR WAVE PROPAGATION





Nonlinearity $\varepsilon = a / h_0$

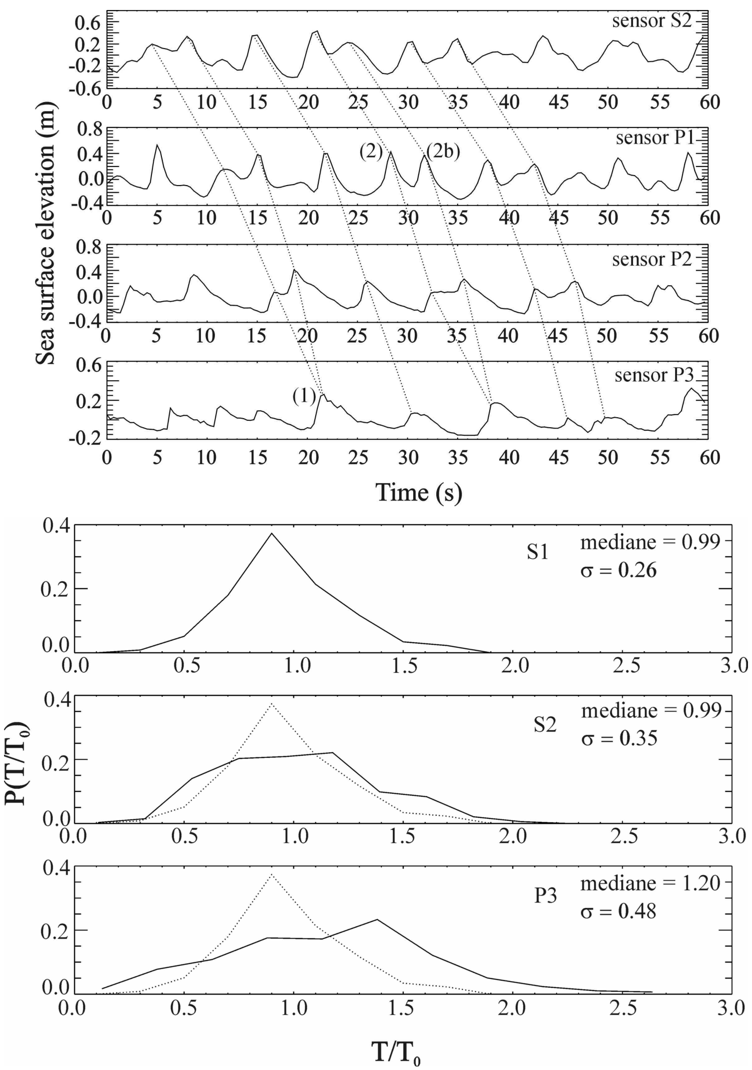
Dispersion $\sigma = h_0 / L$

Long wave (shallow water) models $\sigma \leq 0.1$

II. NONLINEAR WAVE PROPAGATION

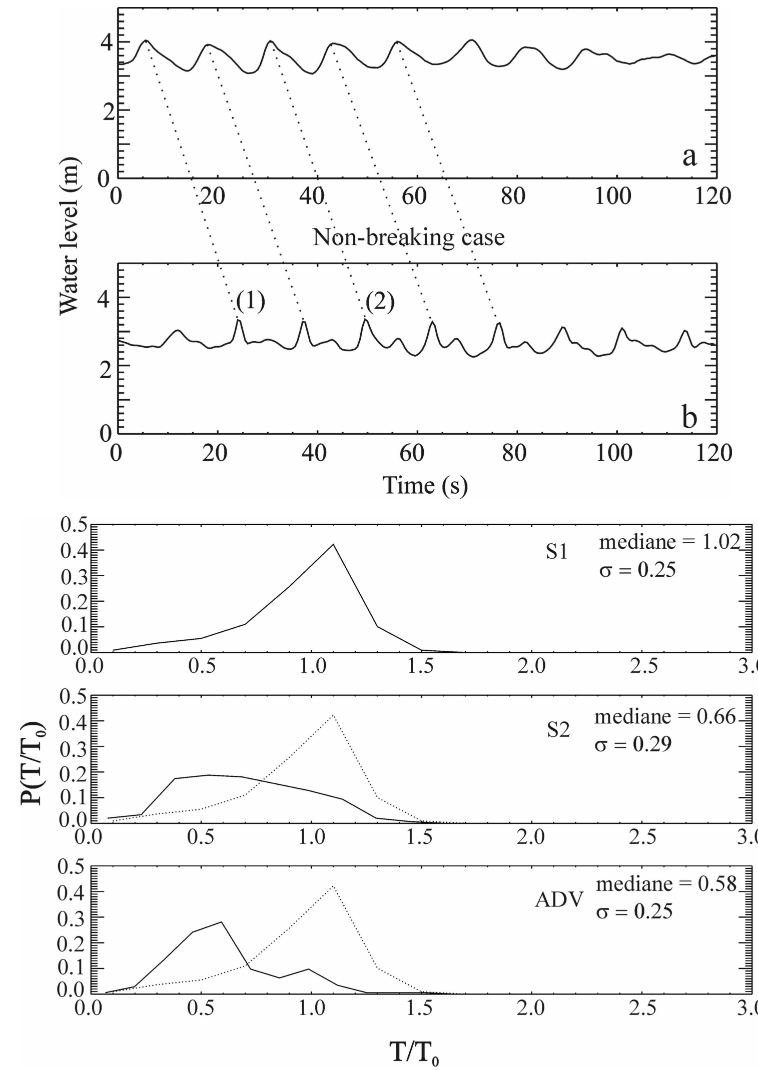
Wave merging in the inner surf zone

Sénéchal, Dupuis, Bonneton (2001)



Higher harmonics release after a bar

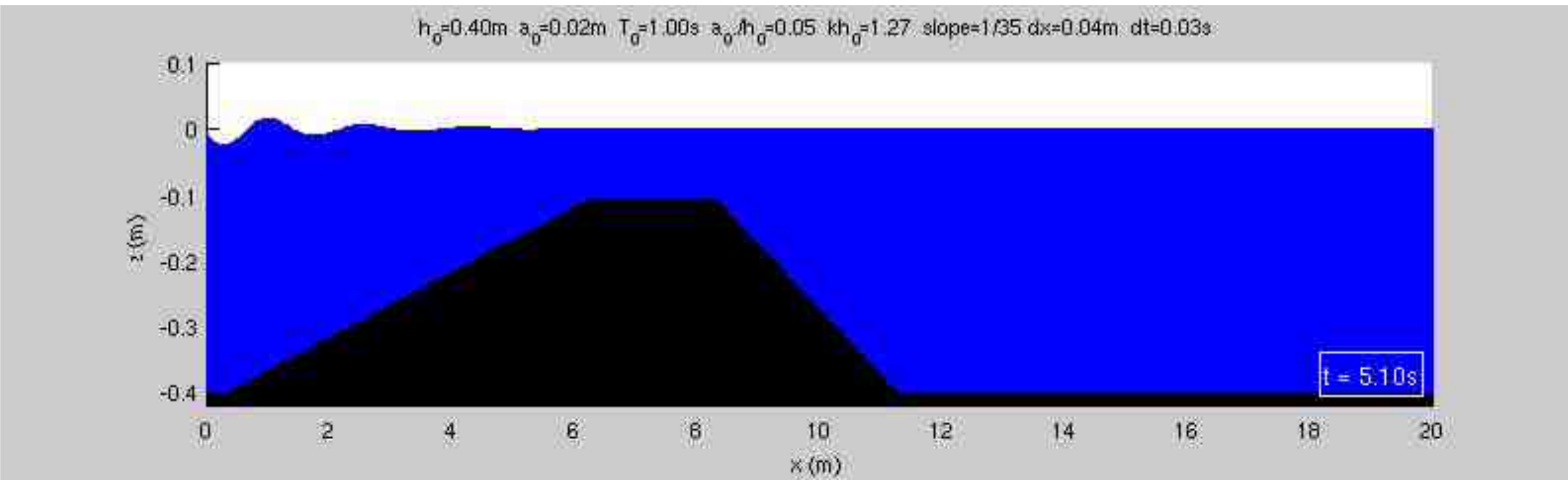
Sénéchal, Bonneton, Dupuis (2002)



Regular waves shoaling over a submerged bar, and higher harmonics release once water depth increases

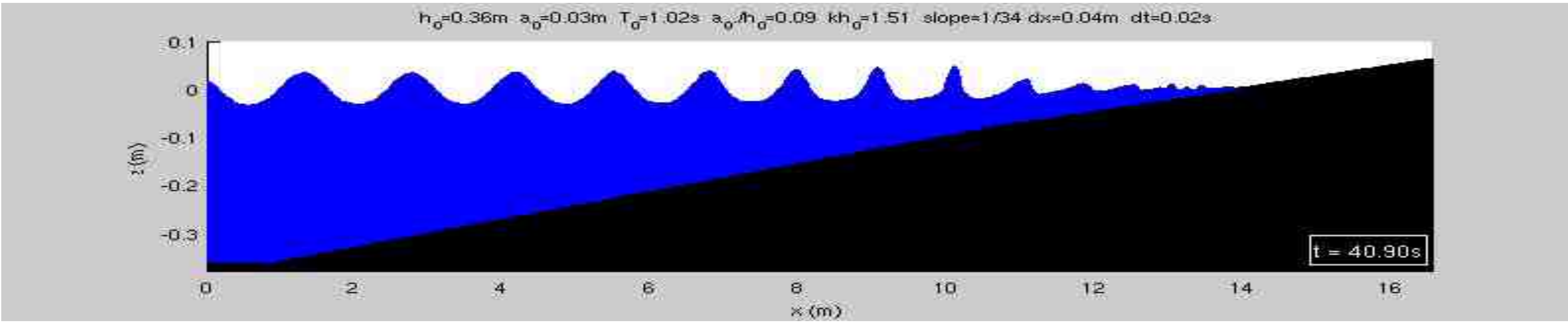
⇒ Generation of bound higher harmonics in the shoal (shallow water propagation)

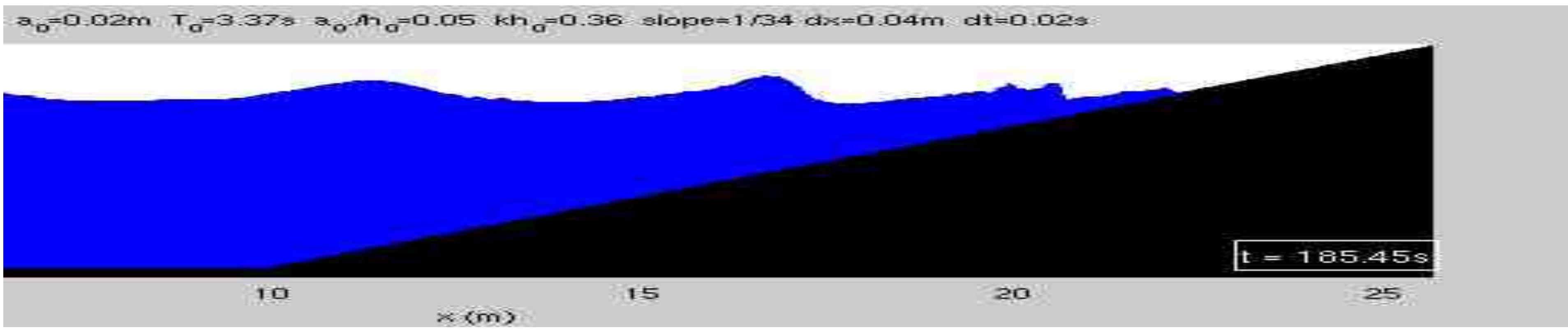
⇒ Over "intermediate" depths, higher harmonics travel at their "own" speed



Source : Cienfuegos et al., 2007 ; Dingemans, 1994 experiments

II. NONLINEAR WAVE PROPAGATION





⇒ **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)**

$$\frac{\partial S_{xx}}{\partial x} + \rho g\left(\bar{\eta} + h\right)\frac{\partial \bar{\eta}}{\partial x} = 0$$

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

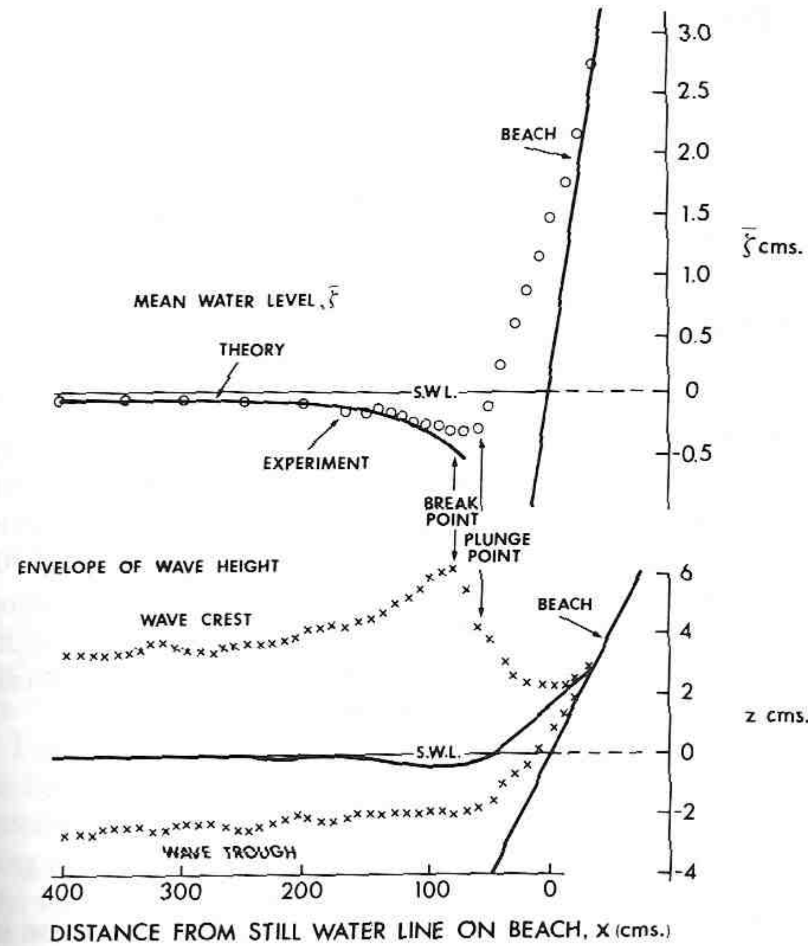


Figure 5.1 Comparison of experiments with theory for set-down and set-up on a plane beach. Data: wave period = 1.14 s; deep water wave height H_∞ = 6.45 cm; breaker height H_b = 8.55 m; beach slope = 0.082 (from Bowen et al., 1968, *J. Geophys. Res.*).

Source : Bowen et al., 1968

Infragravity wave (IG) generation under random wave forcing

⇒ Long waves forced by high-frequency wave groups

<u>2nd Order Long Wave Generation Mechanism</u>

Negative correlation between group envelope and IG waves

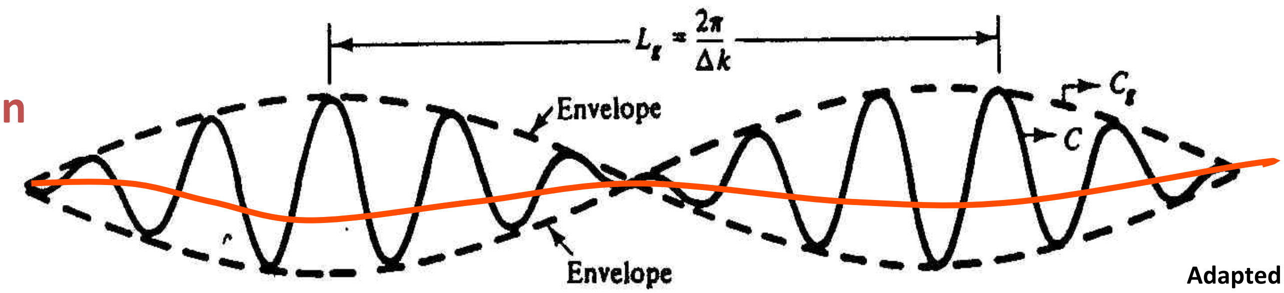


Figure 4.12 Characteristics of a "group" of waves.

Adapted form Dean and Dalrymple, 1984

Mean water level pulsation associated to wave groups' set-up/set-down (Longuet-Higgins and Stewart, 1962)

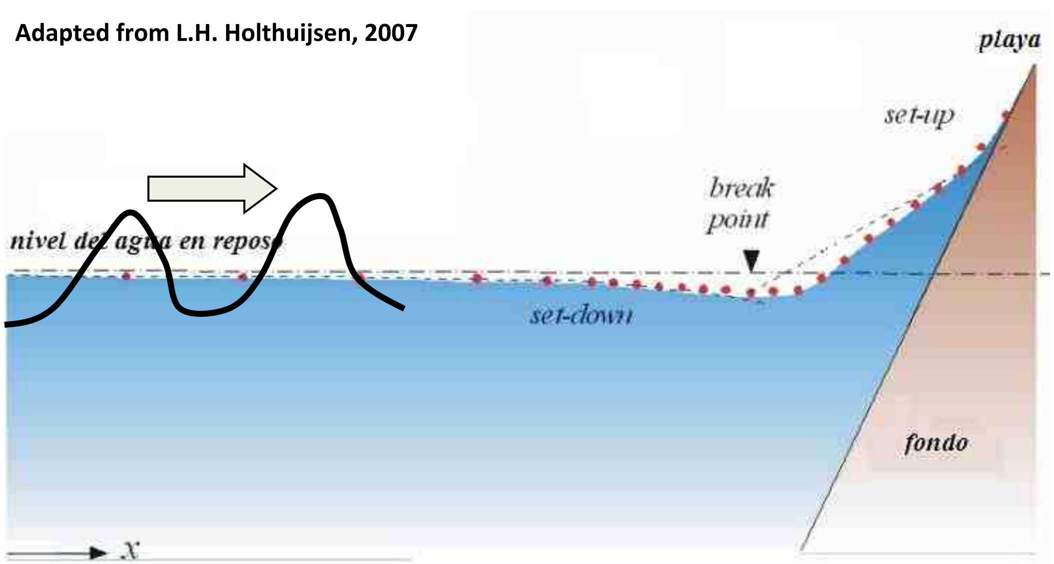
⇒ Bound long waves propagating at group velocity

Infragravity wave (IG) generation under random wave forcing

⇒ Long waves forced by a variable breakpoint location

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

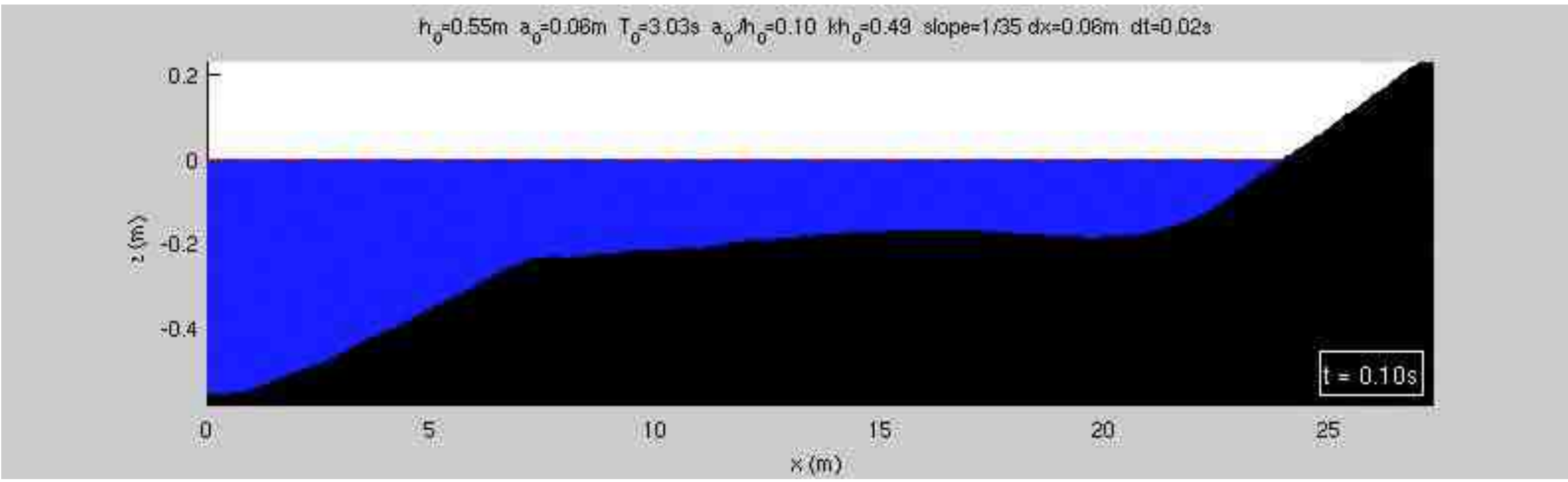
Adapted from L.H. Holthuijsen, 2007



Positive correlation between group envelope and IG waves

SURF BEAT (Symonds, 1982)

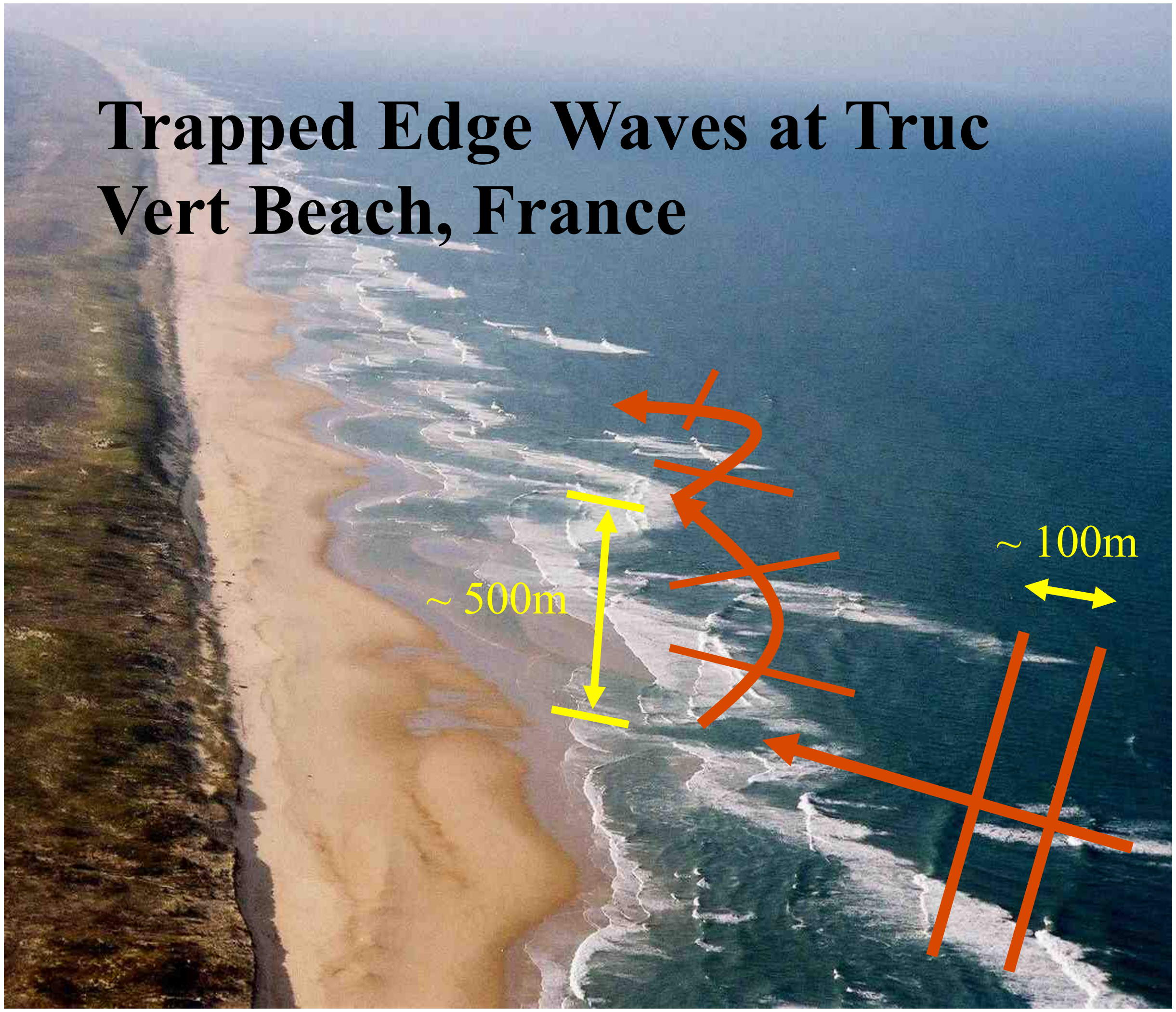
Practical consequences of IG waves: Increased run-ups



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

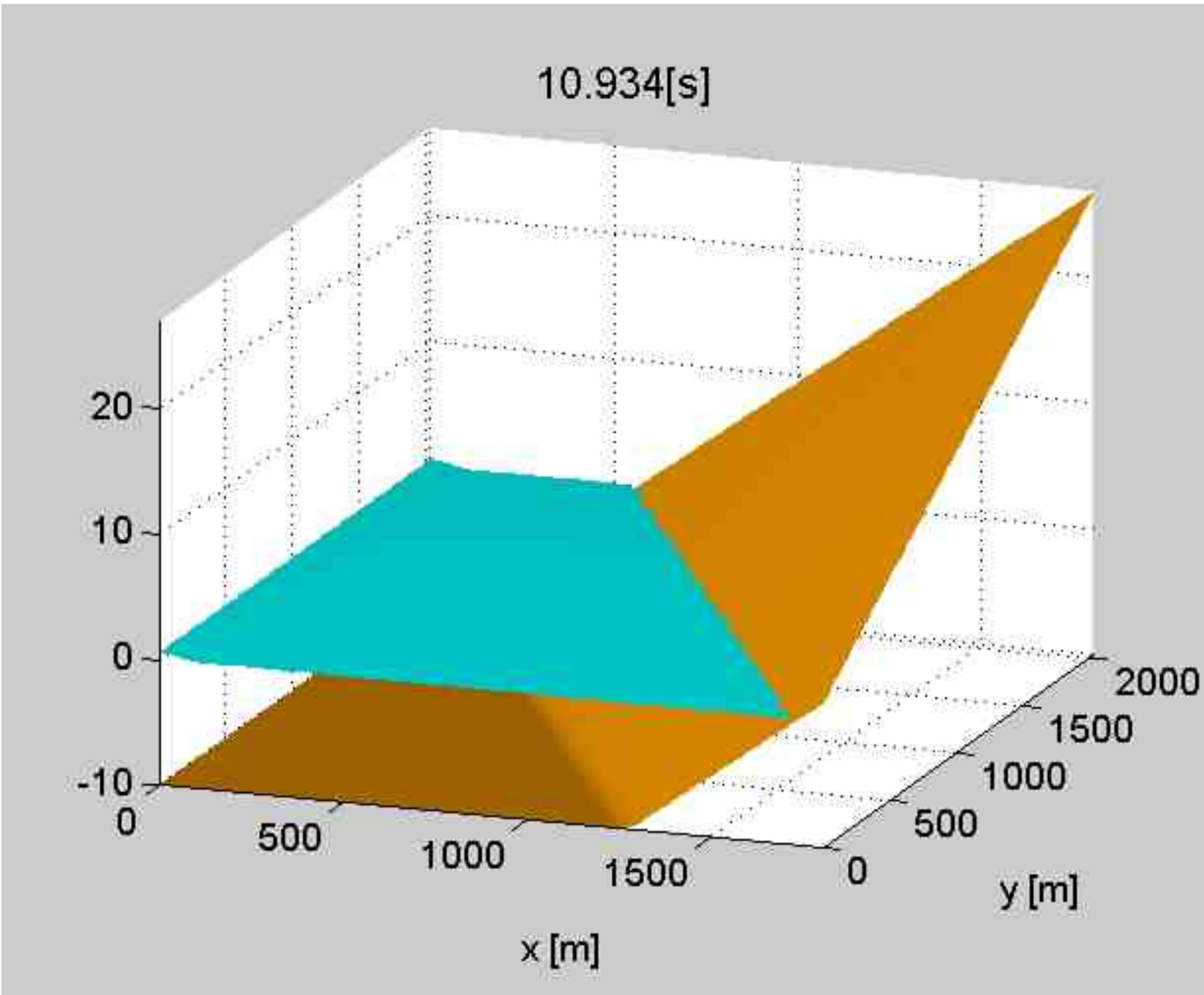
⇒ **Very important for swash zone dynamics and maximum observed run-ups**

Practical consequences of IG waves: Edge waves



- 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 ; θ_0=30°

Uniform beach profile:
h_0=10 ; s=1/40

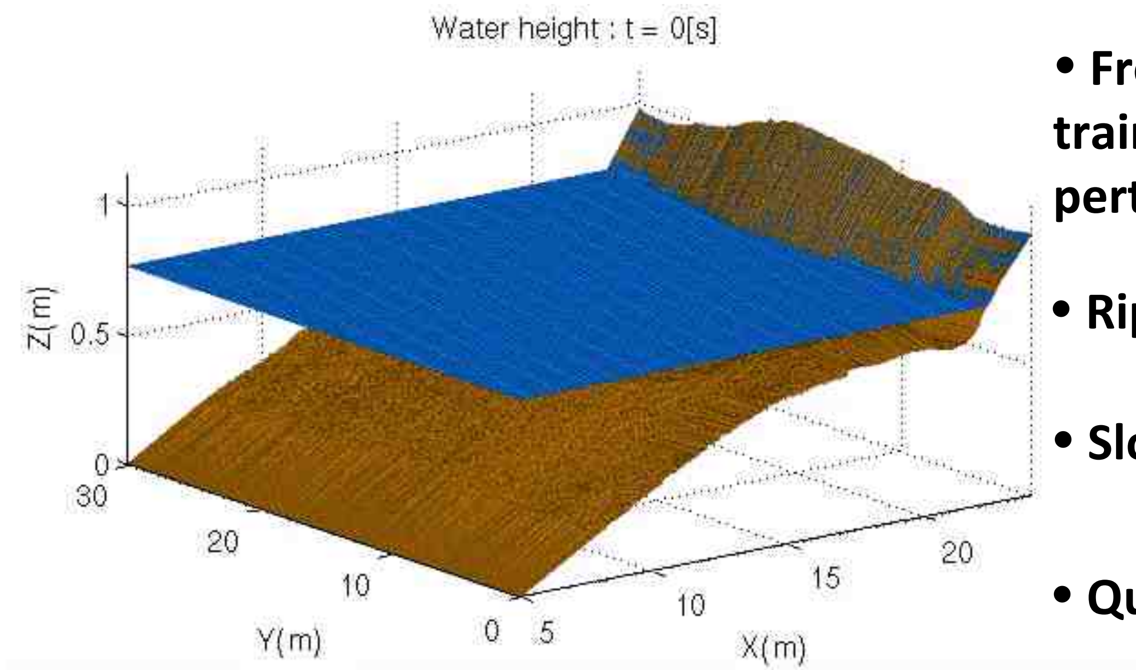
⇒ Reflected waves are trapped and propagate in the alongshore direction

⇒ Important consequences for maximun run-up distribution

NSWE FV model developed by M. Guerra (PUC MSc thesis)

Numerical simulation by José Galaz (PUC undergrad student)

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

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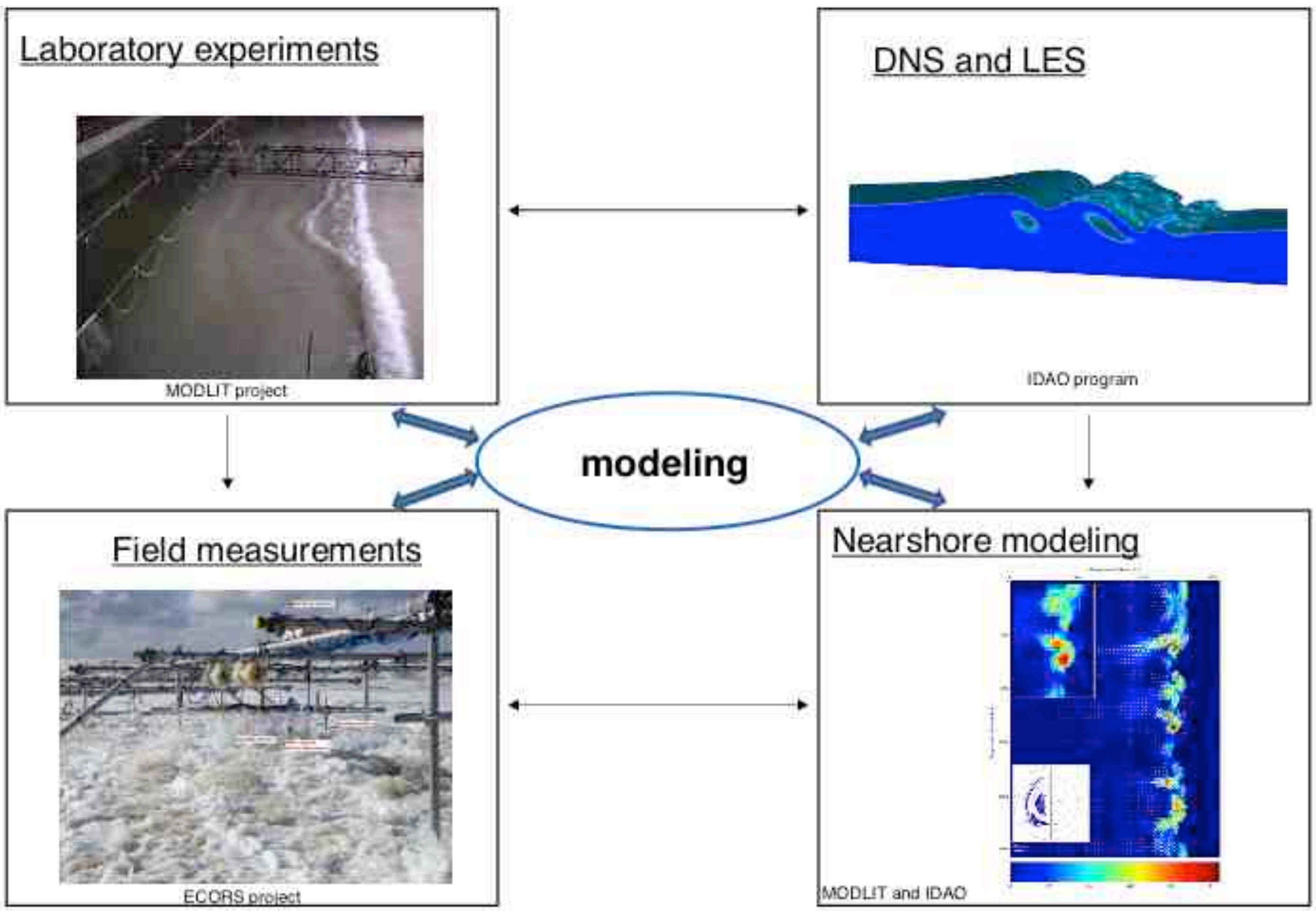
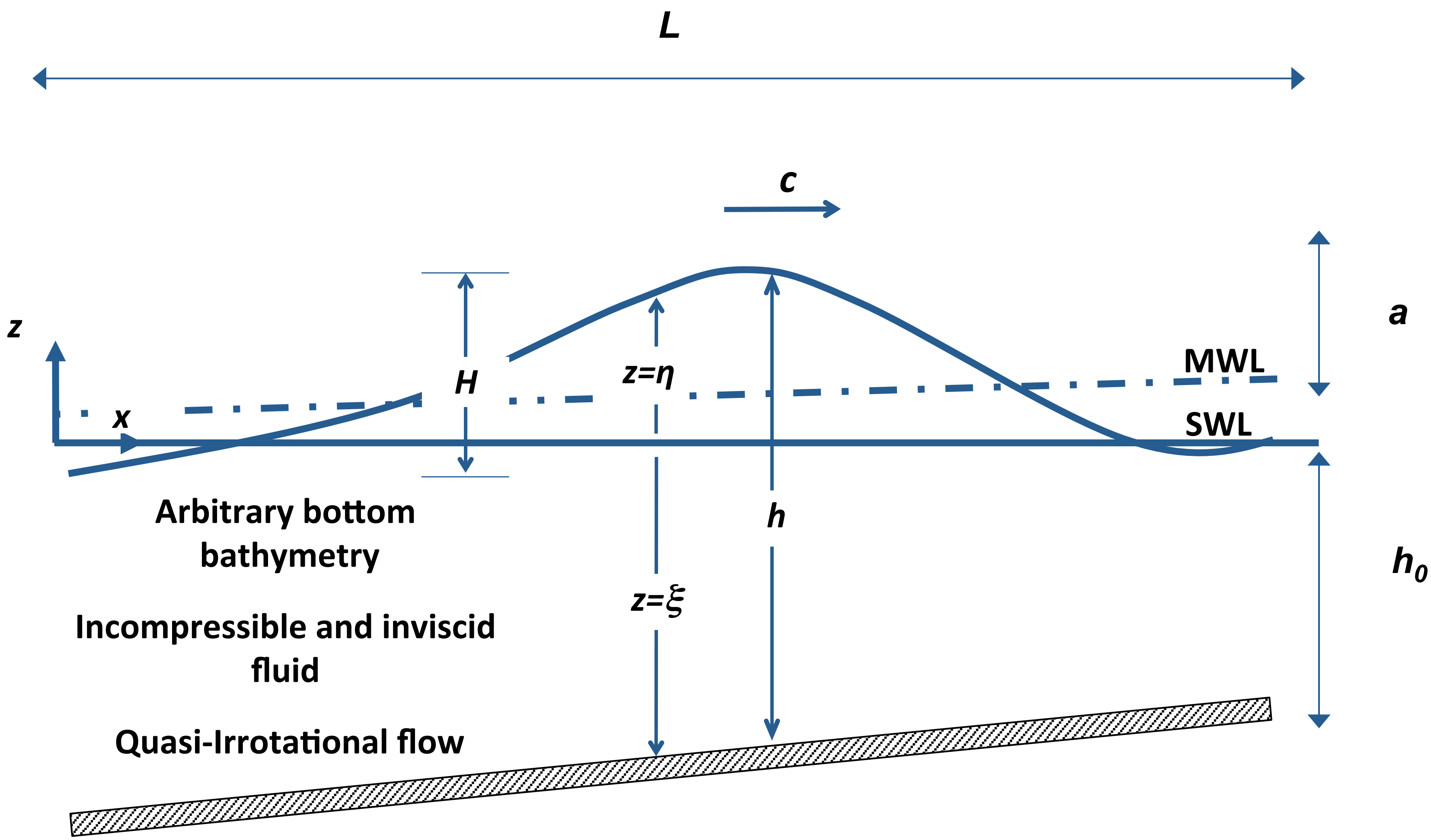
Different methods to cope & understand water waves



Source: P. Bonneton, 2010

General Definitions and Framework



Non-dimensional depth-averaged mass and momentum equations

$$h_t + \varepsilon\left[h\overline{u}\right]_x = 0$$

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

Nonlinearity $\varepsilon = a / h_0$

Dispersion $\sigma = h_0 / L$

Where the pressure field is written as :

$$p(x,z,t) = \left(\varepsilon\eta - z\right) + \varepsilon\sigma^2 \int_z^{\varepsilon\eta} \Gamma\left(x,z,t\right) dz$$

and the function Γ represents the vertical acceleration of fluid particles :

$$\Gamma(x,z,t) = \frac{Dw}{Dt} = w_t + \varepsilon\left(uw_x + \frac{1}{\sigma^2} ww_z\right)$$

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)

$$h_t + \varepsilon\left[hu\right]_x = 0$$

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

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

Where :

$$P(x,t) = -h\left(u_{xt} + \varepsilon u u_{xx} - \varepsilon u_x^2\right)$$

$$Q(x,t) = \xi_x\left(u_t + \varepsilon u u_x\right) + \varepsilon \xi_{xx} u^2$$

Dropping overbars for simplicity

A 4th Order FV S/G-N Model (Cienfuegos et al., 2006, 2007)

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

$$\begin{cases} h_t + F_x = 0 \\ q_t + G_x = 0 \end{cases}$$

With the following definitions for flux functions and auxiliary variables

$$F = hu$$

$$G = uq + g(h+\xi) - \frac{1}{2}u^2\left(1+\xi_x^2\right) + hu_x\xi_x u - \frac{1}{2}(hu_x)^2$$

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

$$r = (h_x + \xi_x)\xi_x + \frac{1}{2}h\xi_{xx}$$

Incorporating Breaking Energy Dissipation (Mignot and Cienfuegos, 2009; Cienfuegos et al., 2010)

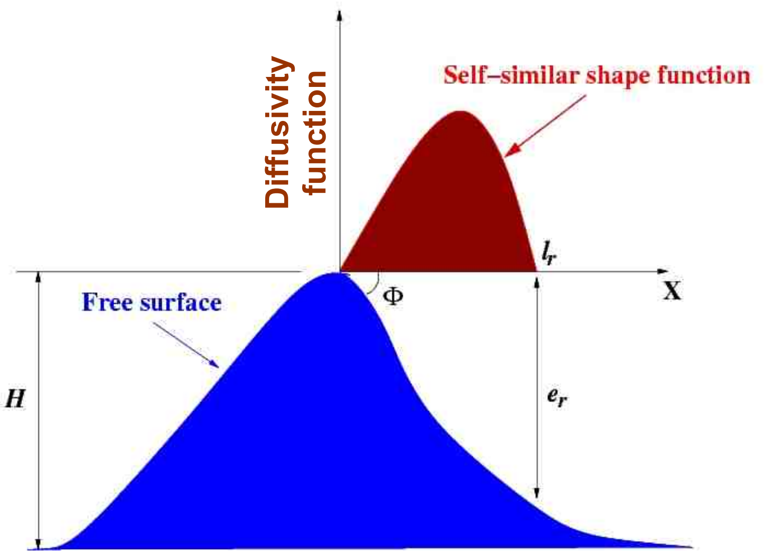
- **Diffusive-like terms in both, mass and momentum conservation equations**

$$\begin{cases} h_t + F_x + D_h = 0 \\ q_t + G_x + \dfrac{1}{h} D_{hu} = 0 \end{cases}$$

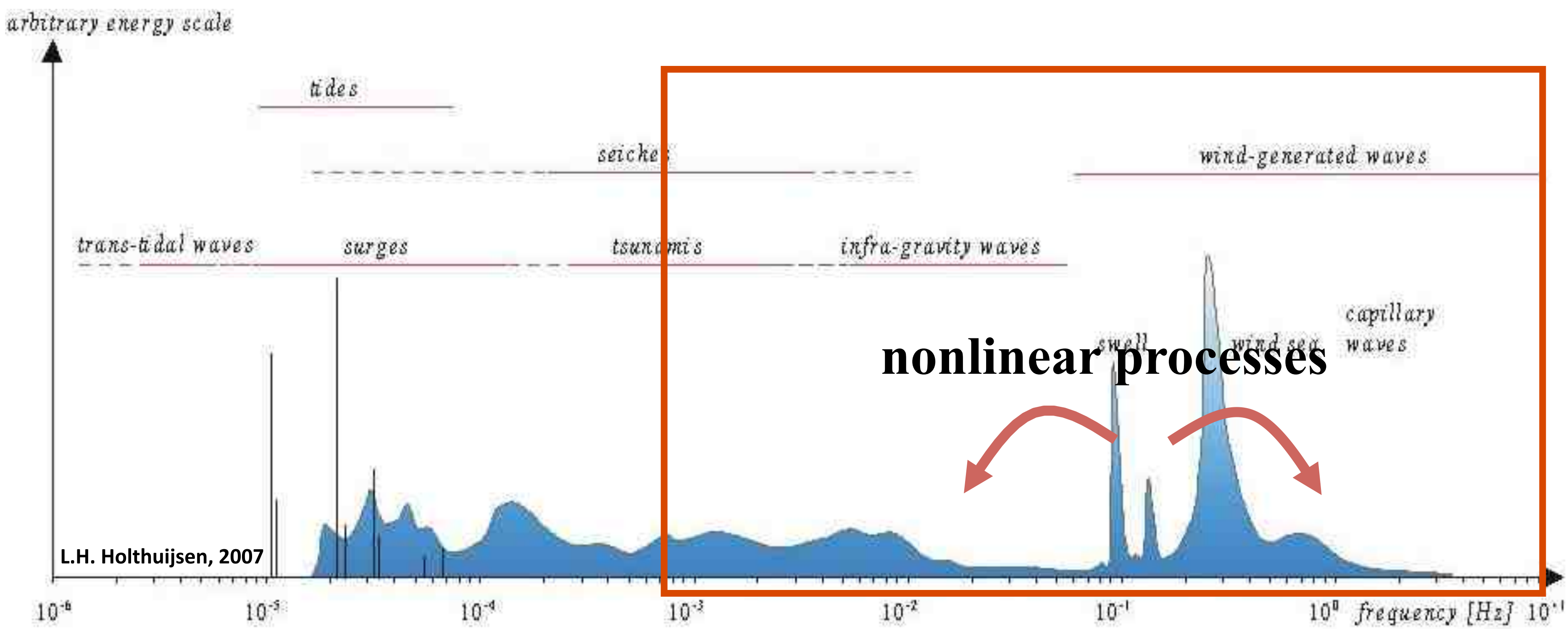
$$D_h = \left(\nu_h h_x\right)_x$$

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

Local re-distribution of mass and momentum below breakers



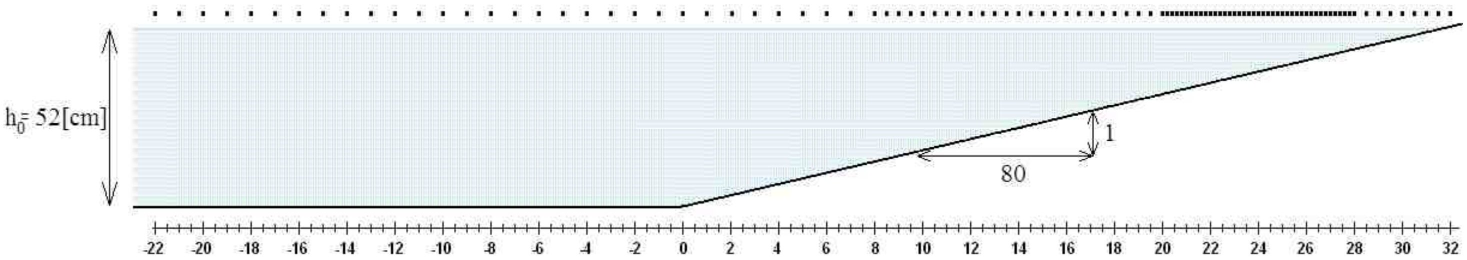
Similar to Kennedy et al., 2000



- 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

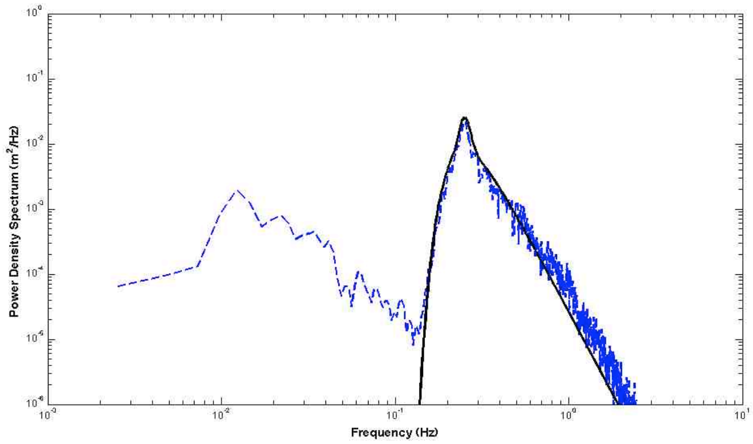
- **Jonswap spectrum (Hasselmann, 1973) for incident wave field**

Tp=4 s (0.25Hz) ; H_{mo}=18 cm ; h_0=52cm

- **Without phase structure (uniform random distribution [0,2π])**

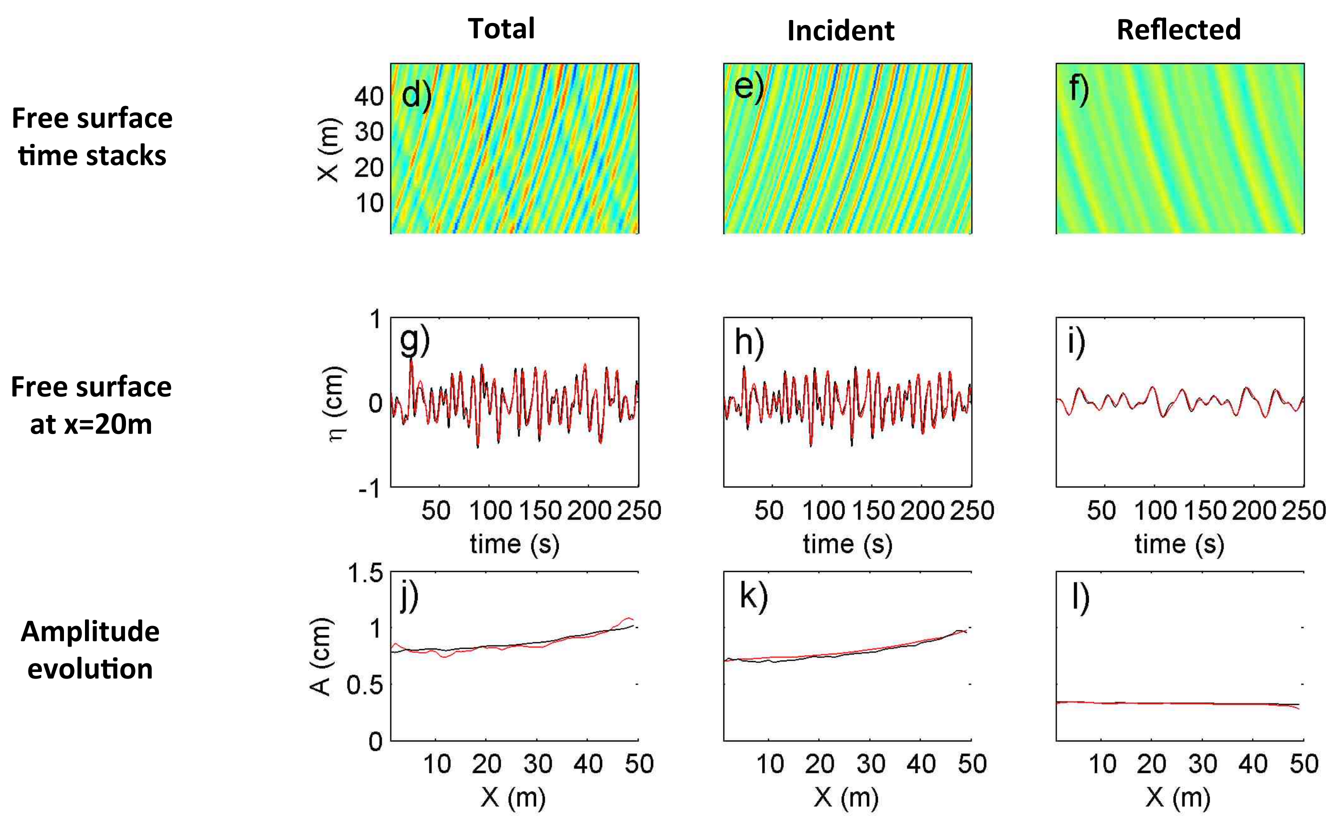
- **Highly nonlinear shallow water regime**

⇒ 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)**

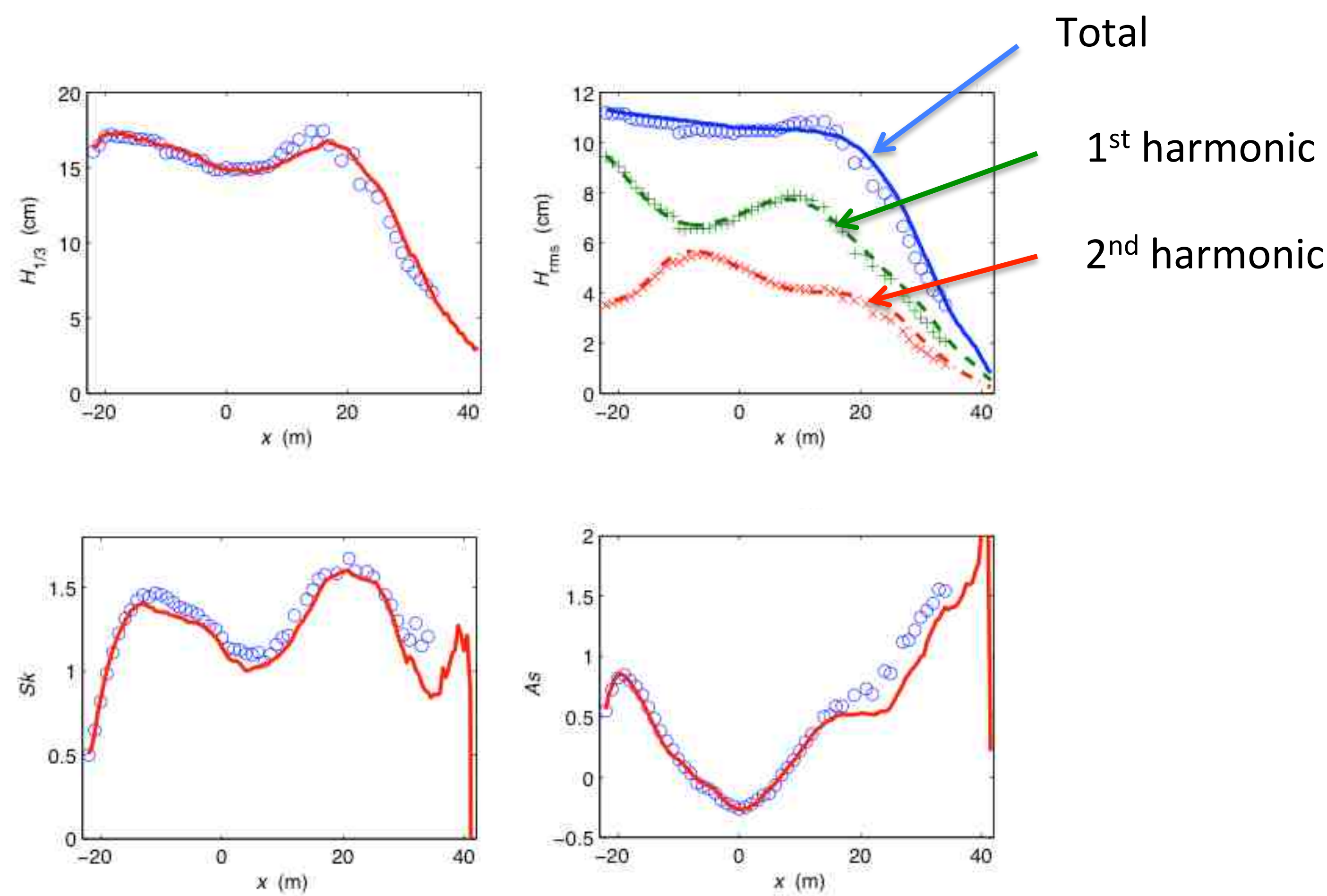


Model Performance on High Frequency Waves

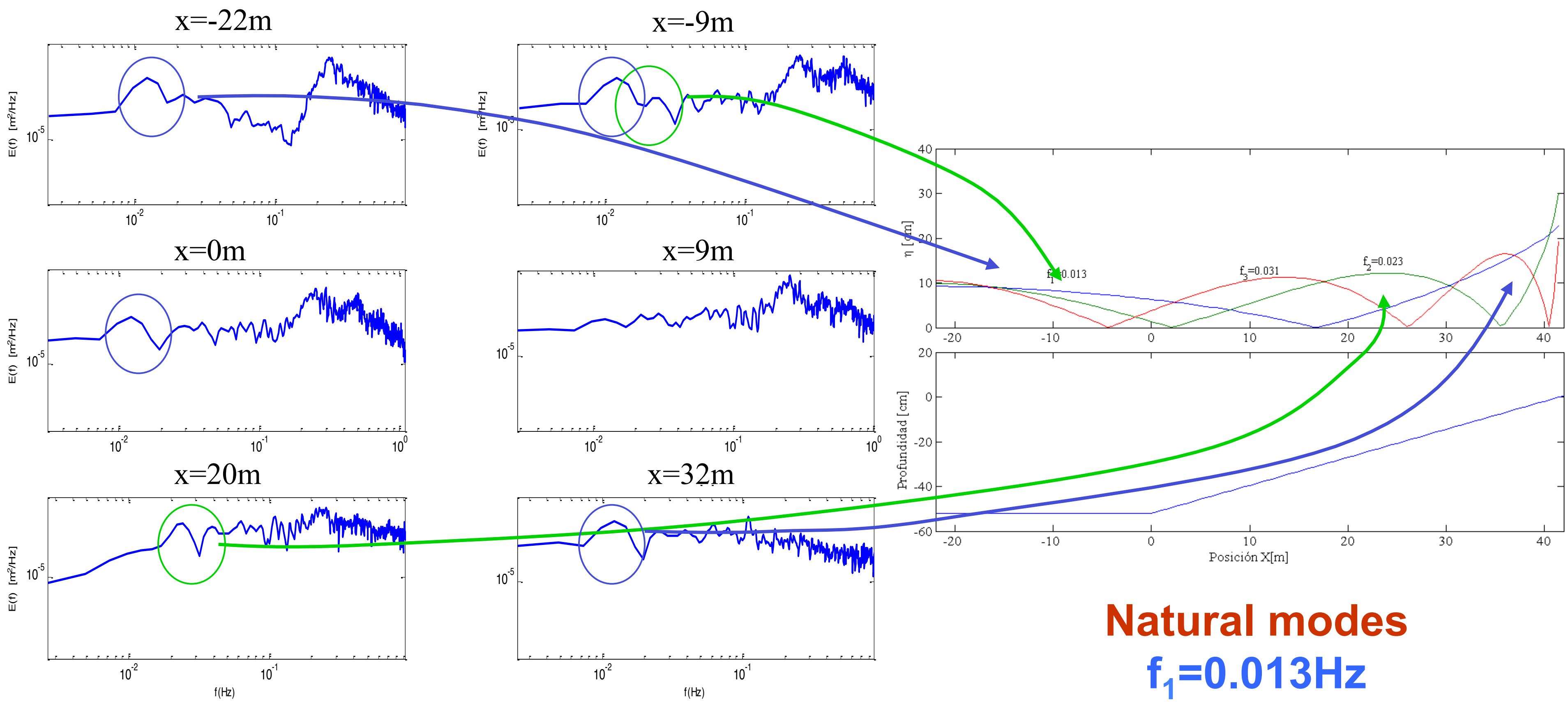
Wave height and energy distribution

Crest-trough wave asymmetry (Sk)

Left-right wave symmetry (As)



Spectral Energy Evolution Along the Experimental Flume



Natural modes

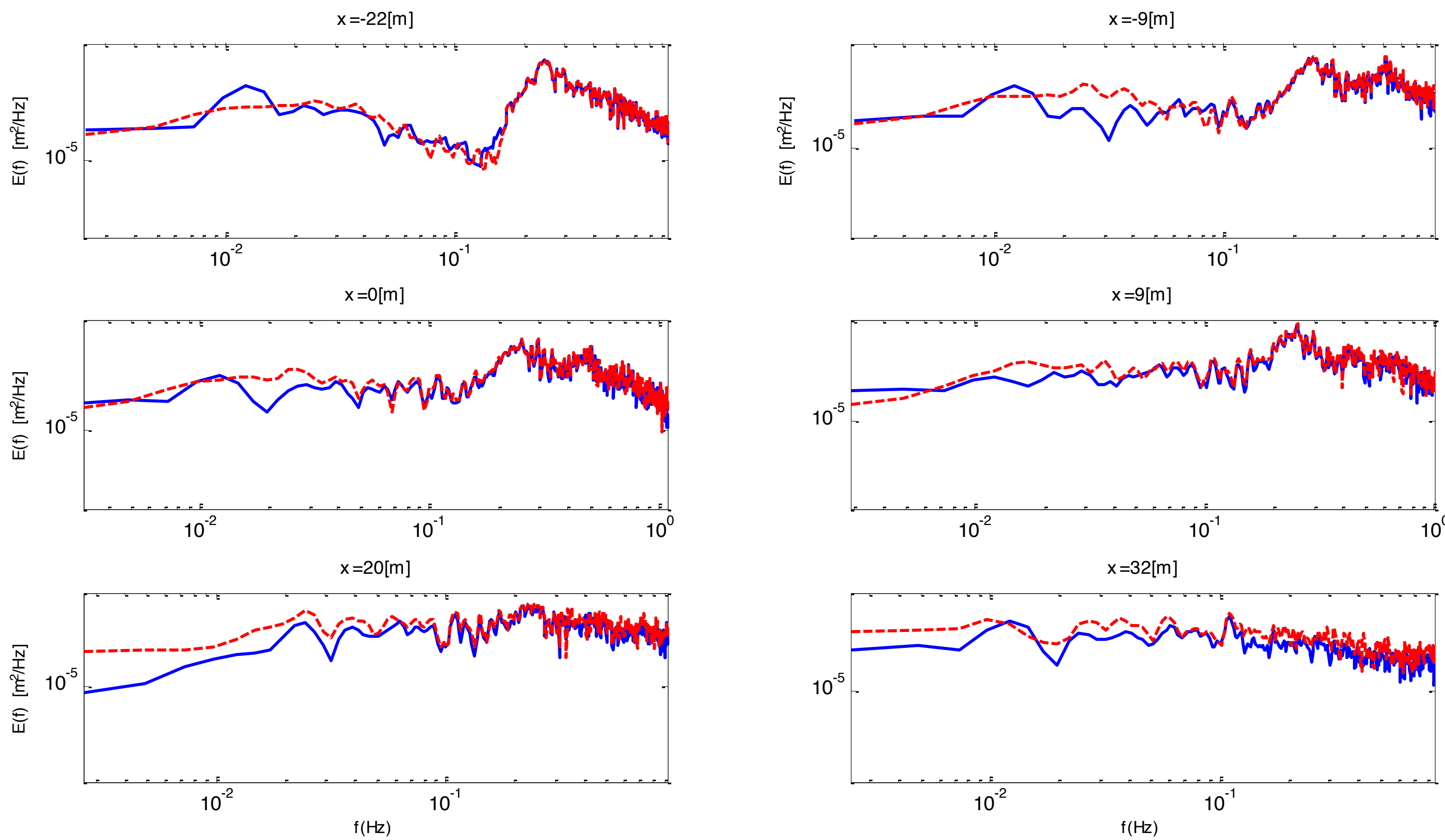
f_1=0.013Hz

f_2=0.023Hz

f_3=0.031Hz

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

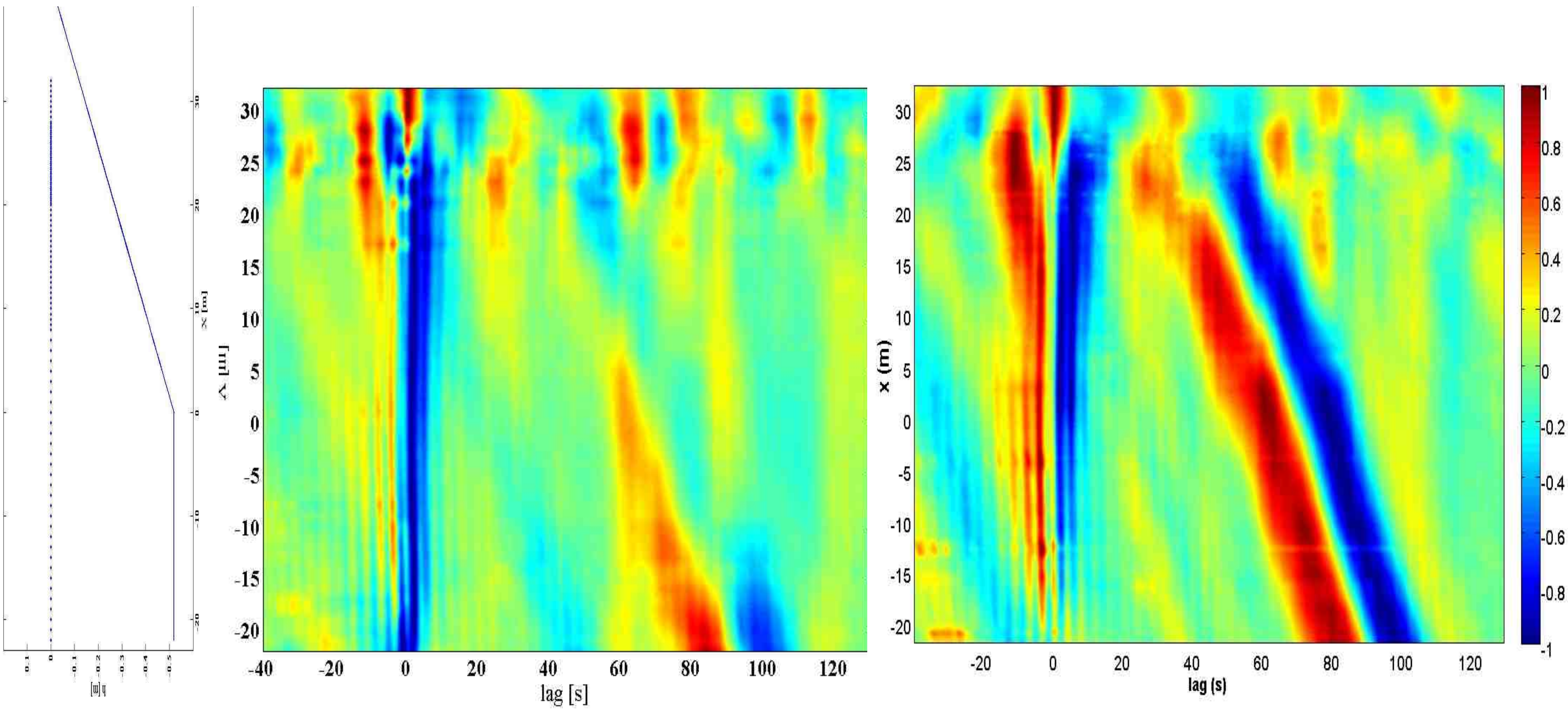
Model Performance in Spectral Energy Evolution



Blue: Experiments
Red : Model

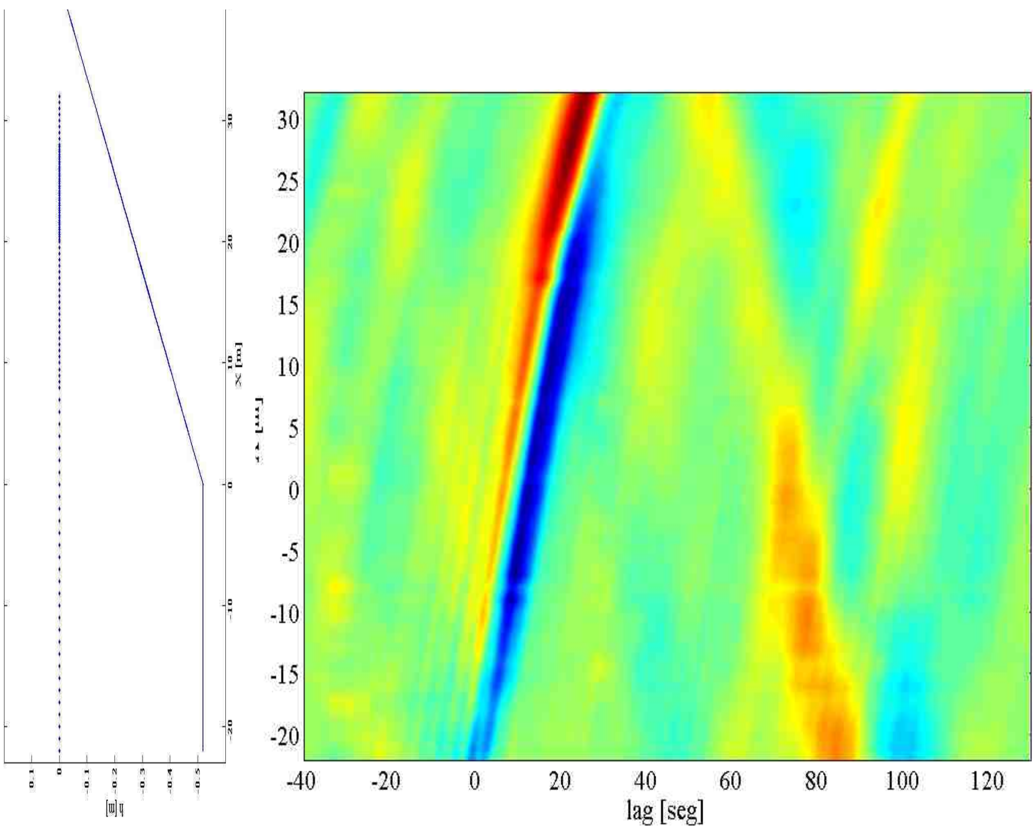
⇒ The model succeeds in transferring energy to higher harmonics and IG waves but no clear modal selection (open boundary condition)

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

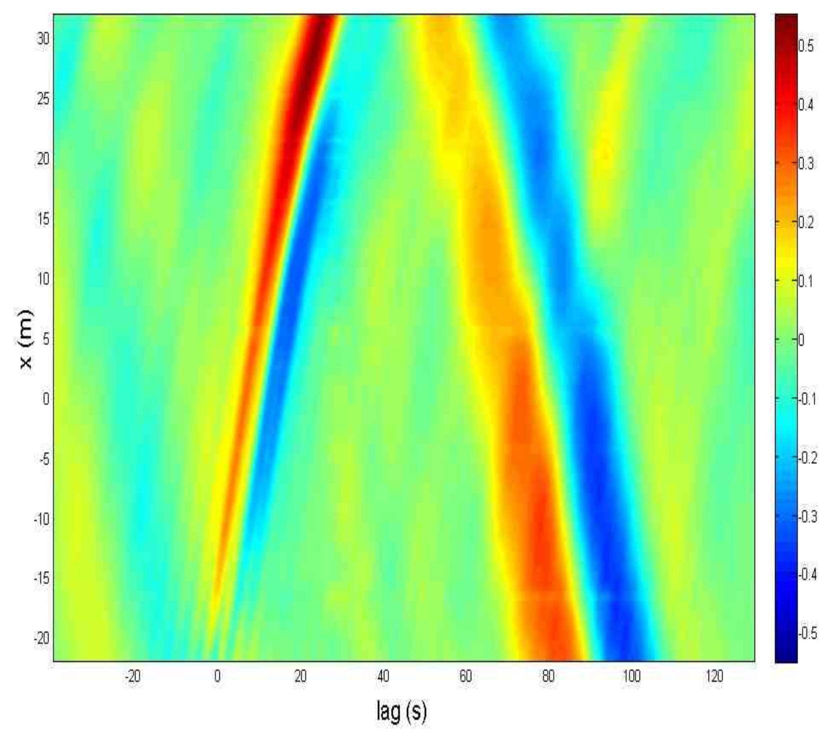


- Experimental
- Numerical

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)

- **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

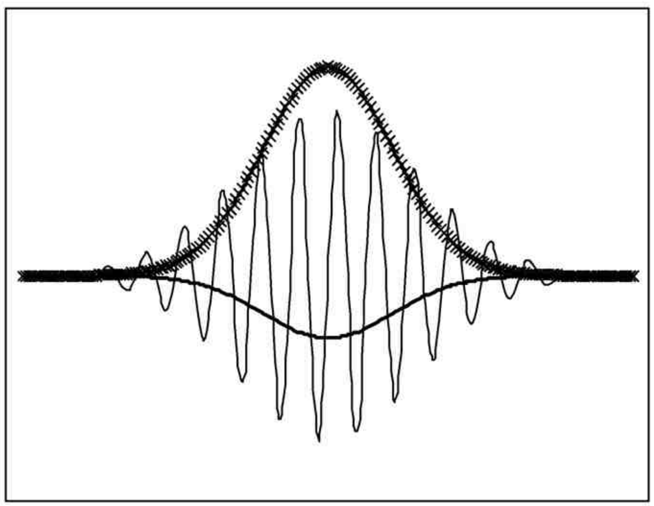


Fig. 1. Steady, bowl-shaped long wave (solid line) driven by a steady, non-resonant wave group (thin line) with S_{xx} varying as indicated by −×−.

Resonant condition

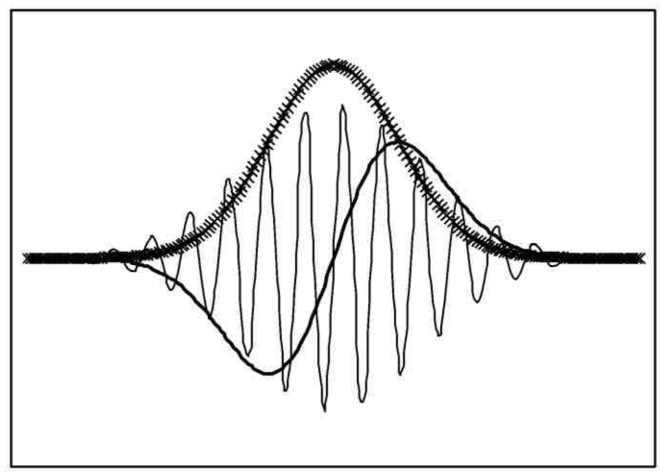
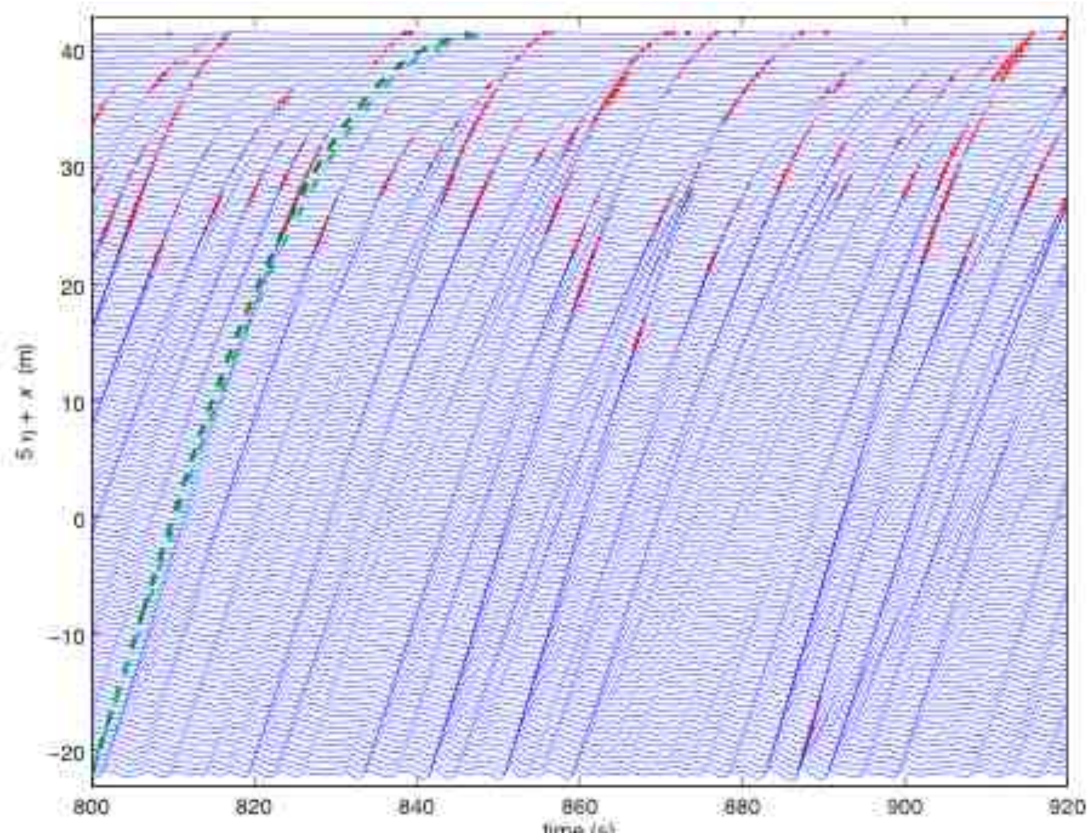
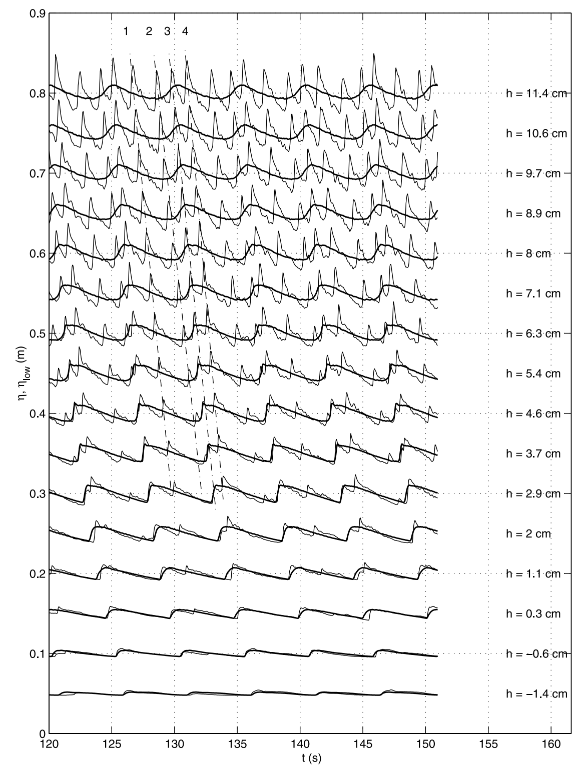


Fig. 3. At resonance, $c_g = \sqrt{gh}$, which happens in the shallow water limit, the Gaussian shaped S_{xx} forcing −×− from the wave pulse generates an И-shaped long wave which grows linearly with time.

• **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)**

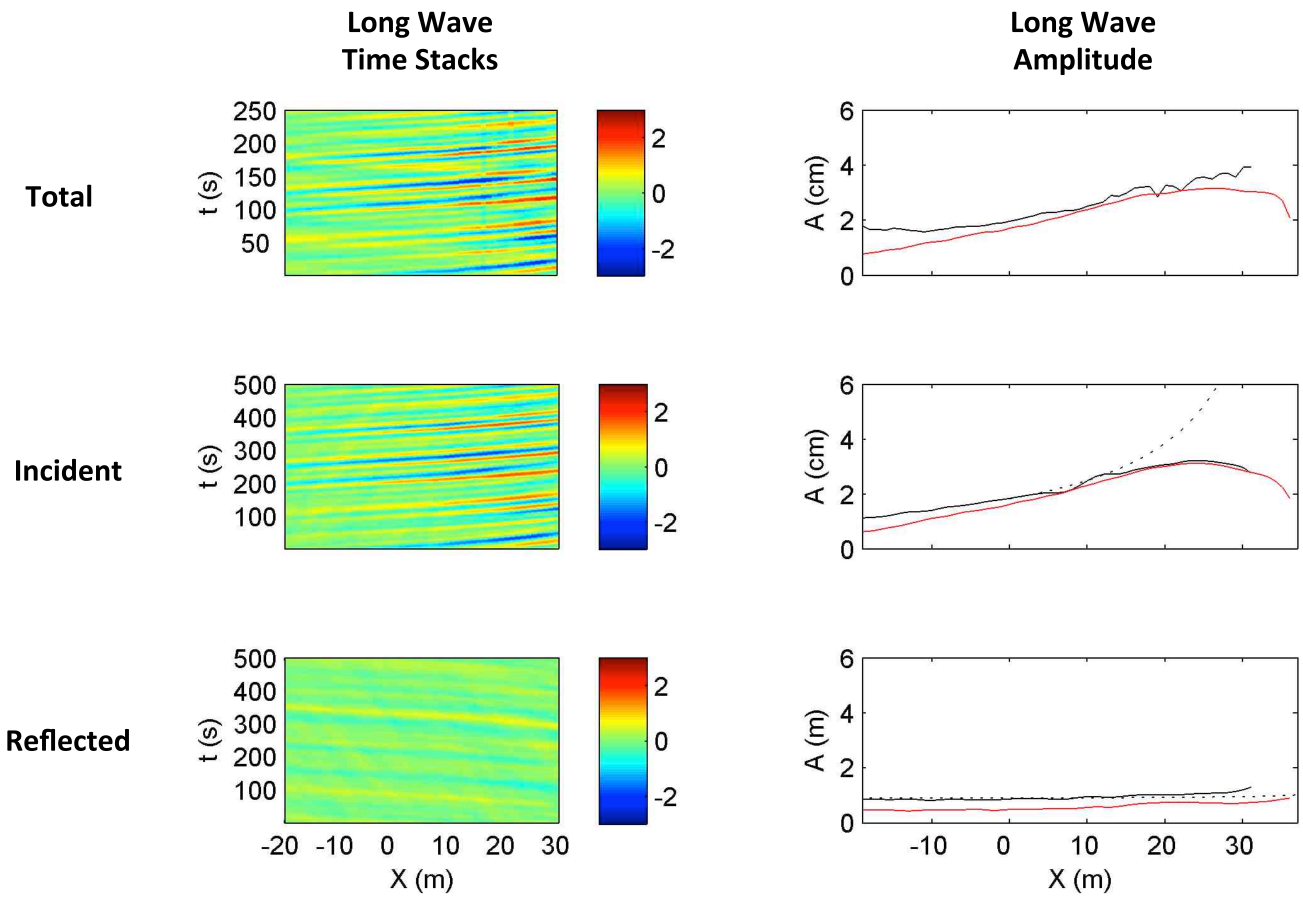


Free surface time series at different locations along the numercal wave flume



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

Model Performance for Incident and Reflected IG Waves



⇒ **Under estimation of incident IG wave**

⇒ **Good representation of incident IG wave generation and shoaling**

⇒ **Under estimation of reflected IG wave**

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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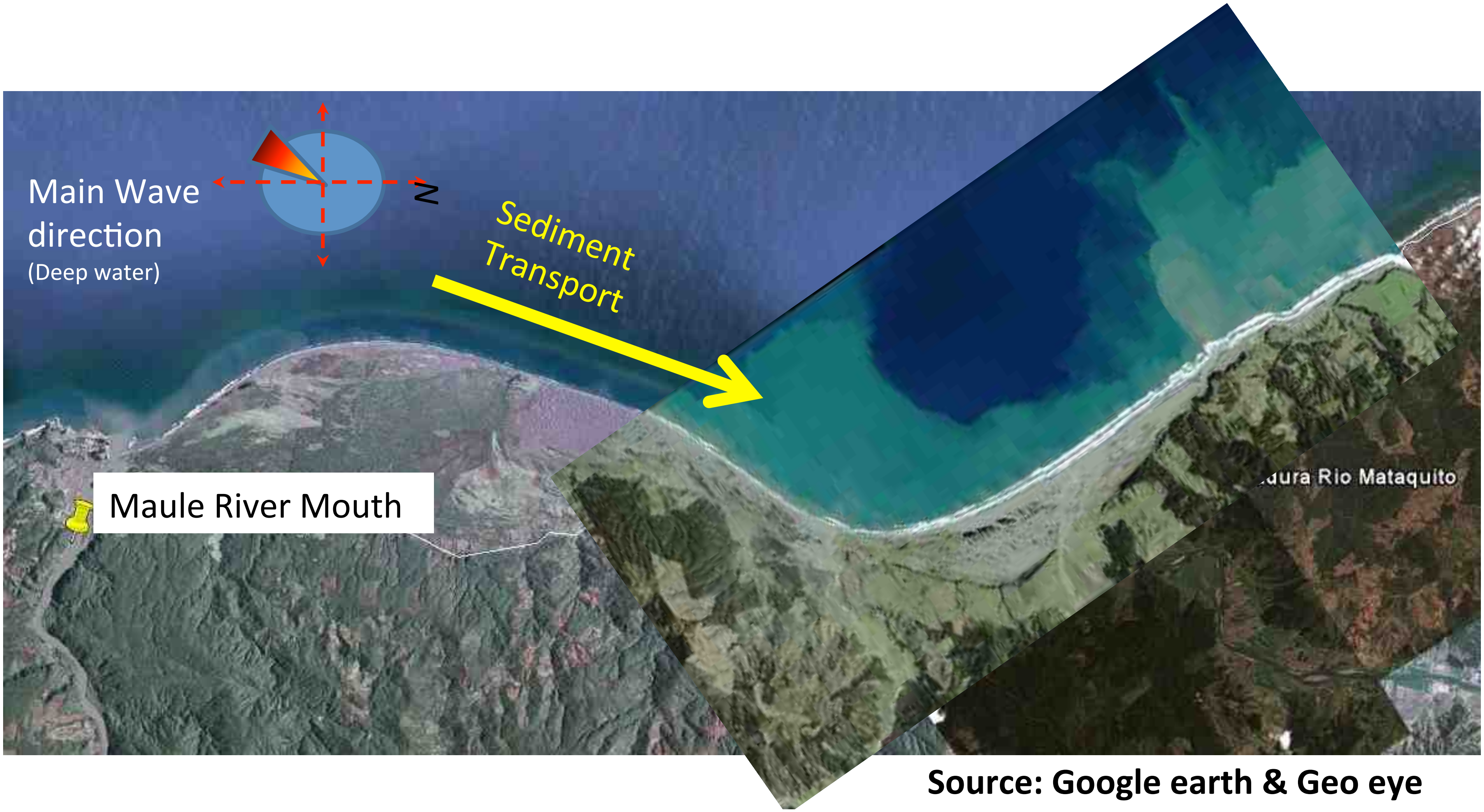
Mataquito River Mouth in the Maule Region



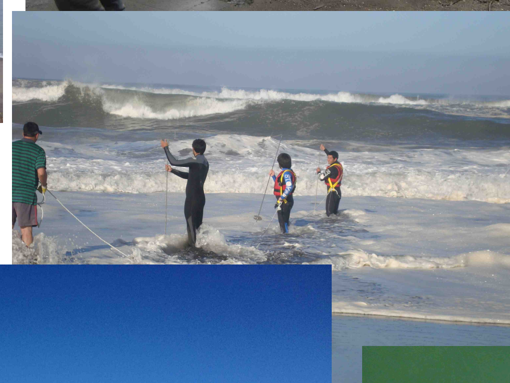
Source: Google earth & Geo eye

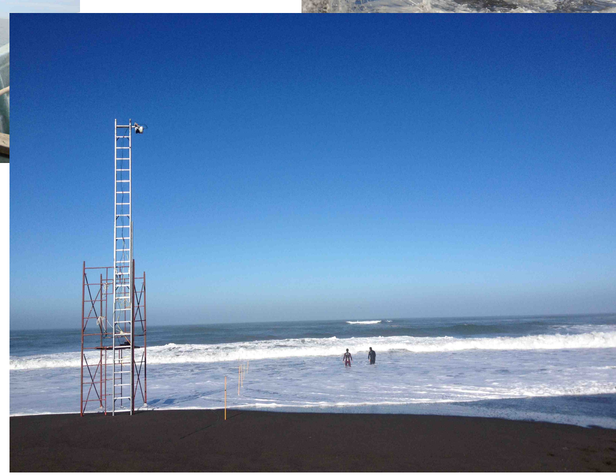
This area was heavily affected by the 2010 Tsunami

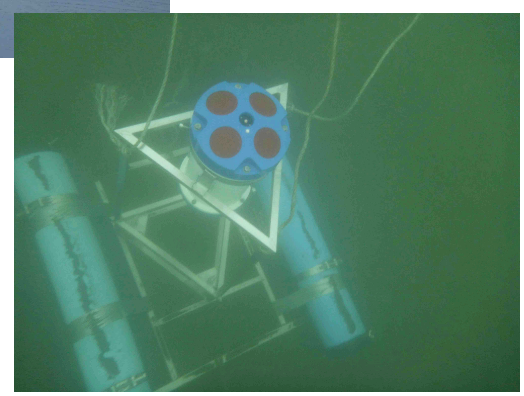
- The land subsided (~0.5-1.0m)
- The sand spit was washed away by tsunami waves
- The sand spit rapidly reformed under highly energetic waves (strong wave and aeolian alongshore sand transport)
- Three years of low river discharge

⇒ The sand spits reformed but different than before

IV. Natural Coastal Laboratory







IV. Natural Coastal Laboratory

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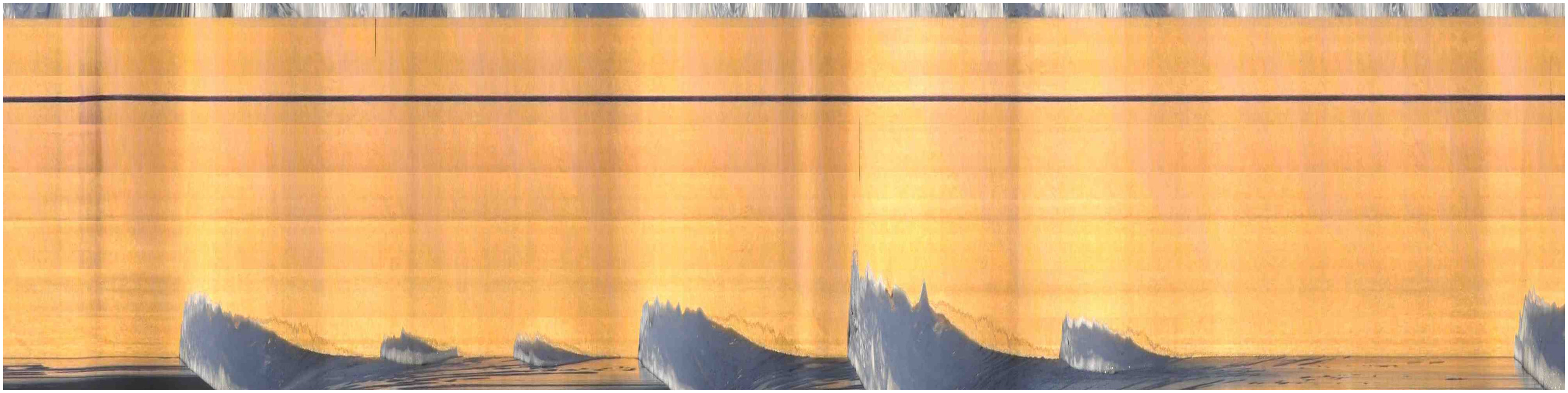

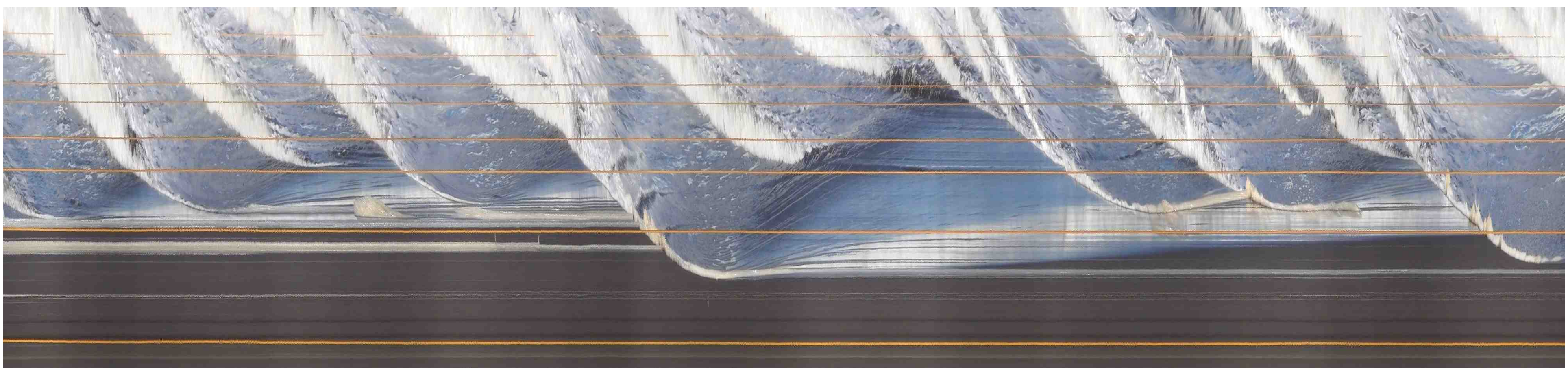

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