Coral Reefs, Mangroves and Coastal Structures

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Earthquake – December 26, 2004
Mag 9, 0.58 GMT, 10 km Deep, 250 km SSW of Banda Aceh, Indonesia

~1 m high Tsunami, 200 m/sec
20-40 min period, ~250 km wavelength
M9.3 Sumatra, Indonesia 2004
MOST Model – PMEL - Titov

Indian Ocean Basin Wide Tsunami

Wave Amplitude (CENTIMETERS)
FACTS Model – PMEL - Titov
Satellite Altimetry and Tsunami Model Comparison (NASA/NOAA)

Before

Banda Aceh City, Sumarta

Digital Globe Satellite Images

After
Mosque at Lhok-Nga, Sumatra: Spontaneous Vertical Evacuation Site

In Lhok Nga 7000 of the town’s 8000 inhabitants lost their lives
Lafarge cement plant before the tsunami was among the major business activities in the area.

- A 35-unit residential complex situated on the coast about 500 meters from the plant, and which housed roughly 100 employees and their families, was completely destroyed.

- 193 employees of the Banda Aceh cement plant were killed or reported missing, while 432 survived.
Banda Aceh

Grand Mosque

Medieval Tsunami Forewarning in Thailand

*Jankaew et al., 2008, Nature*
Medieval Tsunami Forewarning

Jankaew et al., 2008, Nature

Leading Negative N-Wave in Thailand

Siripong, 2006, Earthquake Spectra Special Issue
Leading Negative N-Wave in Thailand

Phi-Phi Island

Before Tsunami

Initial Withdrawal
Sri Lanka Tsunami Survey
Circular Island Experiment (WES-USACE) with trapped edge wave wrapping around lee side (Yeh et al., 1994, Nature)
Queen of the Sea Line
Deadliest (1700+) Train Disaster
Flow Depth Marks: Debris in Trees
Sri Lanka Tsunami Survey

Tsunami Arrival Times

Clock recovered in Galle

Local time UTC + 6 h
Leading Positive N-Wave in the Maldives

Male Atoll and International Airport
Male Atoll and International Airport

Male International Airport
Male Breakwaters and Seawalls
Reethi Rah Resort hit by Tsunami
Aerial Photo Dec. 26, 2004
Reethi Rah Resort hit by Tsunami
Reethi Rah Resort Island Repairs

Figure 3. Original island and architectural master plan for new Island.

Reethi Rah Resort aerial Jan. 2005
Multi-Hazard Risk Assessment: Vilufushi
Cyclone Hazard Zones: Maldives

Multi-Hazard Risk Assessment: Vilufushi
Multi-Hazard Risk Assessment: Vilufushi

![Hazard Zoning Map](image1.png)

Damage Zone

![Composite Intensity Index](image2.png)

Kandholhudhoo Island (Raa Atoll)
Kandholhudhoo – Video

Kandholhudhoo – Video
Kandholhudhoo Island (Raa Atoll)

Kolhufushi Island, Meemu Atoll
Hinnavaru Island, Lhaviyani
Maldives and Sea Level Rise

H.E. Mr. Maumoon Abdul Gayoom, President of the Maldives, speech on dangers of sea level rise, 1987: “The death of a nation”

- Extremely low elevation-1.5m above MSL
- Infrastructure damage and economic impacts
- Food security
- Damage to coral reefs
- Water resources
- Human health

Underwater Cabinet Meeting to Raise Awareness
Ongoing Adaptation Measures

- Male’ seawall: Cost 135 million dollars
- Hulhumale’ Elevation of 2m above MSL at US$3,891,050 per sqkm of elevation 2m above MSL
- Population and Development Consolidation Strategy
- Safer Islands Development
- Coral mining is banned
Far Field Tsunami Surveys

Earthquake History of Hispaniola
(Haiti and Dominican Republic)
12 Jan 2010 Haiti Earthquake Deformation (Calais et al. 2010)

Figure 4 | Deformation observations and rupture model. a, Interferogram (descending track) constructed from images acquired on 9 March 2009 and 25 January 2010. GPS observed (black) and model (red) coseismic displacements. The yellow circles show aftershocks. G = Grosseterre, L = Leogane, PaP = Port-au-Prince. ET = Enriquillo-Plantain Garden fault. The black rectangle shows the surface projection of the modeled rupture. The black-white dashed line is the intersection with the surface. LOS disp. = line-of-sight displacement. b, Total slip distribution from a joint inversion of InSAR and GPS data, viewed from the northwest. c, Interpretative cross-section between points A and B indicated on a. The red line shows coseismic rupture.
Satellite Imagery of Coastal Impact (USGS)
Petit Goave Subsidence

Petit Goave Subsidence
Petit Goave Subsidence

Leogane Uplift
Landslide Tsunami at Petit Paradis in Haiti 2010


Petit Paradis Landslide
Petit Paradis Landslide Tsunami
Petit Paradis Landslide Tsunami

Measured Tsunami Heights in Haiti and the Dominican Republic
Haiti Tsunami Modeling (MOST)

Haiti Tsunami Recordings
Haiti Tsunami Modeling: Jacmel Bay Resonance?

Drawdown at Jacmel Port
- Sri Lankan UN post flooding
Jacmel Flooding of Sri Lankan UN barracks
Jacmel
Haiti Tsunami Modeling: Pedernales, Dominican Republic

Pedernales, República Dominicana
Eyewitness Interview

Haiti: 2010 tsunami CONCLUSIONS

• EQ shaking and sea level draw down as natural warning
• NO spontaneous self evacuation, lack of awareness
• Short inundation distances mostly < 100m
• Maximum flow depth 3m both inside Bay of Port-au-Prince (Grand Goave) as well as South Coast (Jacmel)
• Short wave periods (<1min) inside Bay of Port-au-Prince (landslide tsunamis)
• Longer periods (~5min) along South Coast
• importance of community-based tsunami education and awareness programs both in Haiti and Dom. Rep.
Acknowledgments

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1 April 2007 Solomon Islands tsunami
Solomon Islands tsunami measured heights, runup, landlevel

Co-seismic Uplift of Ranongga

- 82 km of uplifted coastline, predominantly fringing reef
- Uplift up to 3.5 m in the south, decreasing to 1.5 m in the north
- Exposed reef identified as high-reflectivity shore-parallel band

Images courtesy of Geoscience Australia, JAXA/METI
Co-seismic Uplift on Ranongga

Uplifted Reefs as Navigation Hazard
Subsidence - Gizo on Ghizo Island
Landslides on Northwestern Ranongga Island

Mondo village: 60’000 m³ / 2 deaths
Uprooted giant tree on Choiseul

Sasamunga Hospital on Choiseul
Tsunami Education on Choiseul

1 April 2007 Solomon Islands tsunami
1 April 2007 Solomon Islands tsunami

Wallis
Futuna
SAMOA
AMERICAN SAMOA
NIUA TONGA
VAVAU’U TONGA

29 Sept. 2009
M=8.1
Samoan Islands Runup Distribution

MOST-Tsunami Forecast (NOAA/J. Borrero)
Chapter 6: Damming of Waterborne Debris

![Image of debris dam]

Diagram showing the damming of waterborne debris at various locations, including Toma Beach 1, Toma Beach 2, Ve'eloto Beach, Hikuni Point, and Hungaria Tidal Channel.
Niua Islands
Tsunami Survey
Tonga
Nov. 2009

R = 22m Runup, Tafahi
R = 22m Runup, Tafahi Island, Tonga

15 m Flow Depth, Niuatoputapu, Tonga
15 m Flow Depth, Niuatoputapu, Tonga

Chopped Forest
Niuatoputapu, Tonga
9 Tsunami Deaths, Hihifo, Tonga

Mitch, October 1998
Mitch, October 1998

• Heading toward Cuba then veered to Central America
• October 27: stalled off coast of Honduras, winds slowed down to tropical storm strength, but absorbed enormous amounts of water from warm ocean
• October 30: landfall in Central America, tremendous amounts of rain in Honduras and Nicaragua
  – Three-day rainfall totals up to 2 m
  – About 6,500 people killed in Honduras, about 3,800 people killed in Nicaragua, many by mudflows
  – Second deadliest hurricane in history of Americas

Mangrove Deleafing Damage
Erosion & Uprooting Damage

Hurricane Mitch 1998 – Cat. 5
Honduras, Centro America

Mangroves

• tend to grow in low wave energy environments behind coral reefs or in inlets
→ hence multiple factors contribute to the impact reduction image of mangroves
Mangroves

Low Tide  High Tide

• very dense woodwork in the intertidal zone
  → high flow resistance at normal waterlevel
• decreasing flow resistance with increasing surge
  → limited effect on surge and storm waves

Mangroves and Storm Wave Reduction

![Diagram of wave reduction with regions labeled: Region I, Region II, Region III, with incident waves and transmitted waves showing attenuation through the mangrove woodwork.](image)
Nargis Storm Surge Measurements 2008

Fritz et al., 2009
Mangrove Coverage and Land Use

1995

2000
Mangrove Coverage and Land Use
Mangrove Coverage and Land Use

Mangrove Reforestation – Khao Lak (Thai)
Earthquake source deformation (GSI)

Figure from Newman, 2011

Pacific Basin Wide Tsunami Propagation
(Modeling: NOAA, PMEL)
2011 Japan Tsunami Survey (TETJSG)

Mori et al., GRL, 2011 and CEJ, 2012

Fukushima Gap

Fukushima (1) Daiichi NPP
Idagawa – 10 km N of Fukushima NPP
Figure 4 (a)-(d) Tsunami observed at Tsukabara, Minami-Soma, Courtesy Mr. Sadatsugu Tomisawa

(a) 15:39:24


(b) 15:39:28

Figure 4 (a)-(d) Tsunami observed at Tsukabara, Minami-Soma, Courtesy Mr. Sadatsugu Tomisawa

Idagawa before and after tsunami w and w/o pine trees

(a) before tsunami, November 1975
(b) after tsunami, December 2012

Idagawa - delayed survey June 2012
Idagawa - delayed survey June 2012

Idagawa Pump Station
Idagawa - delayed survey June 2012

Idagawa – watermark 15 months after
Tsunami Heights vs Distance from Shoreline

- **Kabaniwa**
- **Obama**
- **Tsukabara**
- **Murakami**
- **Tsunobeuchi**
- **Idagawa**

**Idagawa** 10 km N of Fukushima Daiichi NPP

Distance from shoreline (m)

Tsunami Height (m)

- **Idagawa**
- **Obama**
Onagawa – toppled engineered buildings

April 2011

TLS scanning for detailed runup topography at Yoriisohama
Yoriisohama school girl video of 2\textsuperscript{nd} wave

Photo: Fritz
April 16, 2011
Kesennuma

Photo Credit: Kenji Satake, ERI, University of Tokyo, 12 March 2011

Kesennuma Bay Survey, April 14-16, 2011
Kesennuma Vertical Evacuation Sites

Kesennuma – Japanese Coast Guard (JCG)

Photo Credit: Kenji Satake, ERI, University of Tokyo, 12 March 2011
Kesennuma JCG station video sites LIDAR

Kesennuma JCG station original video
Kesennuma JCG station video sites LIDAR
Tsunami Height Analysis

Kesennuma JCG station video based tsunami currents
Kesennuma JCG station video analysis based tsunami currents

Kesennuma JCG station video sites LIDAR Tsunami Height and Current Analysis

Fritz et al., 2012, GRL
Sanriku Coast GPS-buoy tsunameters

Sanriku Coast Measurements and **Modeling**

Shimozono et al., 2012, CEJ
Hirota Bay and Rikuzentakata surveys between March 22 and April 13, 2011

Liu et al., 2013

Rikuzentakata Inundation Area Comparison for 4 historical tsunamis
Rikuzentakata with Tsunami Control Forest before 2011 tsunami

Rikuzentakata with Tsunami Control Forest after 2011 tsunami
Rikuzentakata Coastal Defenses

SINGLE pine tree out of 70,000 trees of Coastal Tsunami Forest “survived”

Rikuzentakata City and Kesen River

Urban Area of Rikuzentakata

Kesen River

Yahagi River

Osage River

Coastal forest

Hirota Bay

Inland run-up point

Inland inundation point

Max inundation along river
Selected Transects along KESEN RIVER and through RIKUZENTAKTA

Tsunami Height decay along Kesen River: ~1m / km

Rikuzentakata City Sports Complex
Vertical Evacuation Site but building TOO LOW

April 10, 2011
Aneyoshi Relocation after 1896/1933

Aneyoshi: V-shaped valley with R > 38 m

July 2012

April 2011

Miyako up-River tsunami propagation
Kamaishi Tsunami Breakwater

Kamaishi LIDAR survey June 2011
Japan 2011 tsunami CONCLUSIONS

• EQ ground shaking as natural warning; spontaneous and mandated evacuation contains fatalities
• Coastal Defenses and vertical evacuation sites were designed for order of magnitude smaller events
• importance of community-based tsunami education and awareness programs (90% survival rate at Rikuzentakata).
• LiDAR at large scale during follow-up survey
• LiDAR data provide spatial coordinates of control points used for water level analysis, camera motion analysis, video rectification with DLT and PIV processing
• Tsunami runup overland flow exceeding 13 m/s at Yoriisohama
• Measured tsunami outflow velocities up to 11 m/s make navigation impossible

Muchisimas Gracias!
Algunas Preguntas?

Photo: Fritz
April 11, 2011
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