GeoSeas Conference, 9 October, 2012

Coastal Risk: Advance or Retreat

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Coastal Risk: Advance or Retreat

Introduction

Sea level

Tsunami

Extreme storm-induced waves

Breaching

Coastal flood inundation

Coastal Erosion

King Cnut the Great (c. 985 or 995 – 1035) King of England, Denmark, Norway and part of Sweden

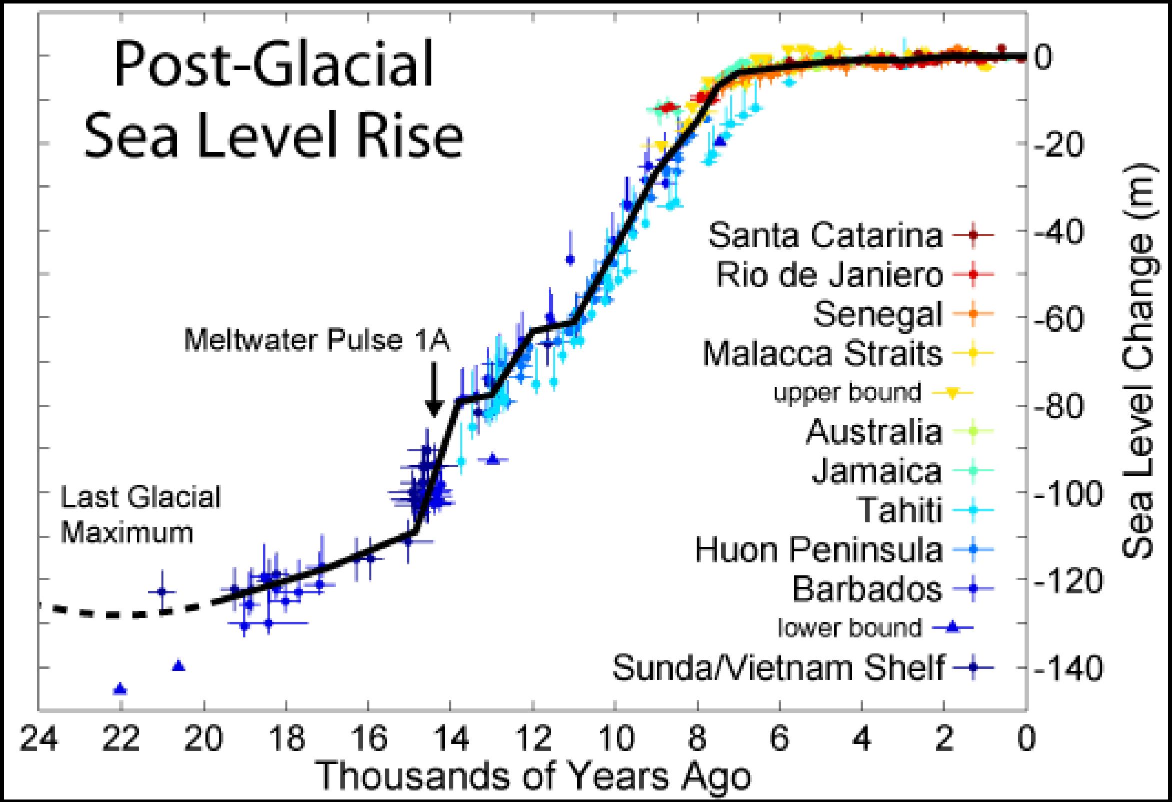
"Let all men know how empty and worthless is the power of kings, for there is none worthy of the name, but He whom heaven, earth, and sea obey by eternal laws"

Mean Sea Level Changes

Global relative sea level change (global eustacy)

Local relative sea level changes

tecto-eustacy, steric-eustacy, bed consolidation



http://globalicwarming.com/sea_levels/ (2009)

Coastal mega-cities are vulnerable to inundation from the sea

Shanghai in 2014….

Artist's Impression, Getty Images, Daylife Publishers (2009)

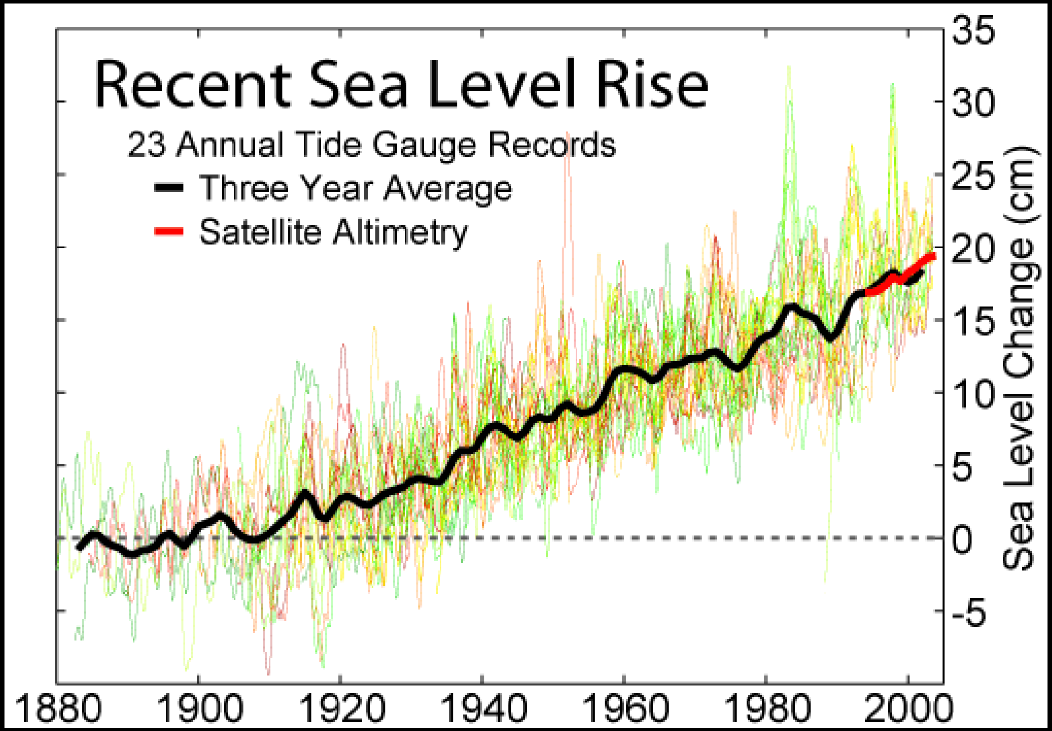
Mustang Beach, Texas ….

Marine Advisory Service,Texas A & M Sea Grant College (Komar, 1992)

Coastal Flood Risk

Coastal flood risk derives from statistical combination of extreme

tide + surge + waves



http://globalicwarming.com/sea_levels/ (2009)

IPCC global mean sea level rise ~ 0.5 ± 0.3 m in 21st C

Coastal flood risk = probability distn of flood variable x damage

Early Warning Systems for Coastal Flooding

UN International Strategy for Disaster Reduction Secretariat

Early warning systems should comprise

- risk knowledge
- monitoring and warning service
- dissemination, communication, and response capability

Indian Ocean Tsunami (2004)

Aceh, Indonesia

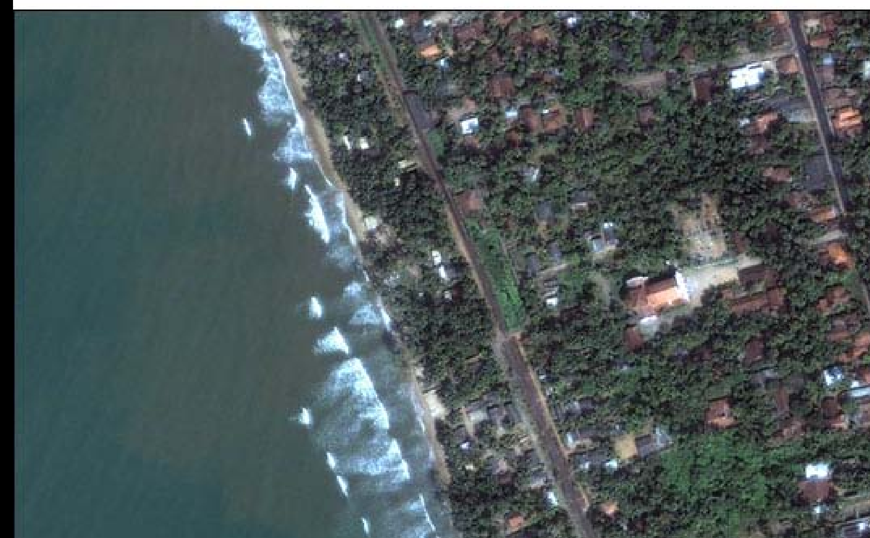
December 29, 2004

January 10, 2003

NASA, Ikonos Images Centre for Remote Sensing, Imaging and Processing, NUS and Space Imaging

Sri Lanka

December 26, 2004



January 1, 2004

NASA, Image Copyright Digitalglobe

New Orleans (2005)

Hurricane Katrina

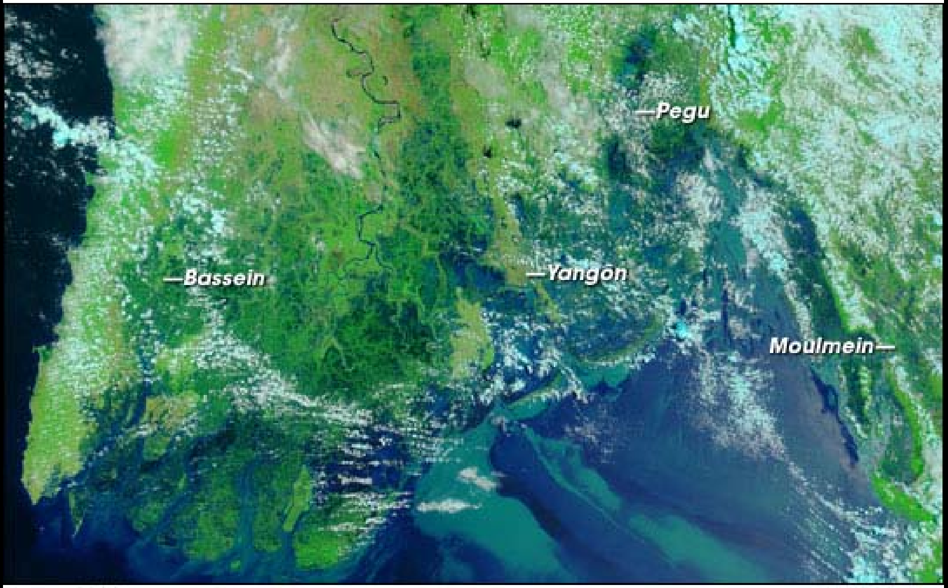
NASA

Storm Surge

www.NOAA.katrina.gov

Cyclone Nargis (2008)

April 15, 2008



May 5, 2008

Images from NASA

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T_R-year return sea level is that which is exceeded once on average every T_R years, determined using a probability distribution of maximum sea levels

Consider coastal defence with design life L years

Design based on crest level z_R with return period T_R

$P(z \geq z_R) = 1/T_R$ where z is max annual sea level

Probability of failure $= 1 – (1 – 1/T_R)^L$

Design return period $T_{RD} = 1 / [1 – (1 – x)^{1/L}]$

where x is the chance of failure

After evaluating T_{RD} then estimate z_R using prob distn

Sea Level

Probability distribution of extreme values invariably tends to one of three forms of Generalised Extreme Value Distribution

$$P(z \le z_R) = \exp\left\{-\left[1 - k\frac{(z-u)}{\alpha}\right]^{\frac{1}{k}}\right\}$$

where k, u and α are parameters

Frequency factor approach

Design crest level, $z_R = z_m + K\,s$

z_m is the mean annual maximum sea level

K is a frequency factor related to T_R for given EVD

s is standard deviation of annual maximum sea level

Sea Level

Coastal engineers usually have < 100 years' data on sea levels, but must extrapolate up to 1000 years depending on asset

Extreme sea levels formed from combination of

astronomical tides (deterministic)

storm surges (random processes)

and affected by trend in mean sea level rise (deterministic)

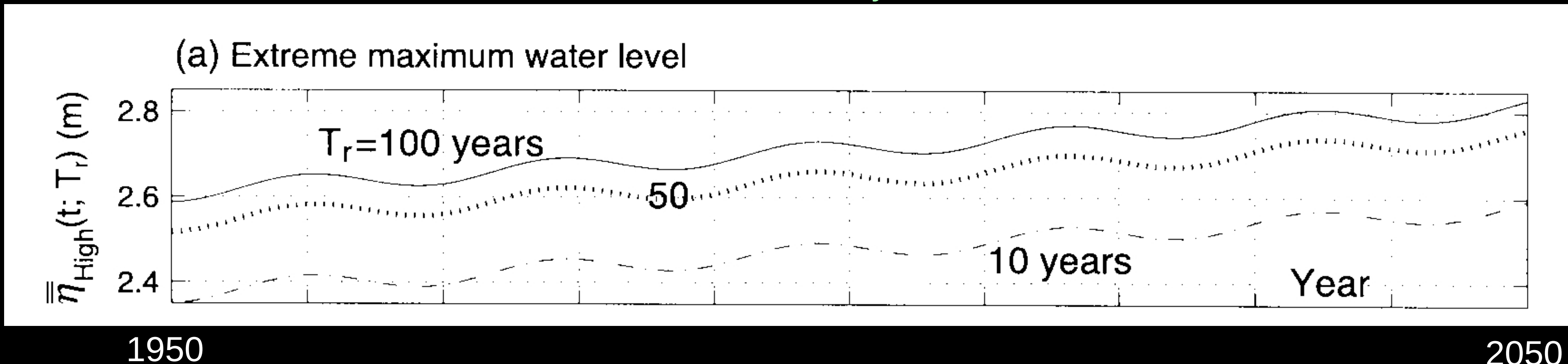
University of Plymouth, UK

Methodology for data series of monthly max and min sea levels (Sobey, 2005)

1. Subtract trend and major astronomical tidal forcing from data series
2. Shift remaining surge data according to mean higher high water level or mean lower low water level
3. Fit shifted data to EVD
4. Estimate magnitude of storm surge event for given T_{RD}
5. Reverse datum shift, and estimate extreme sea level from

$$z(t;T_R) = z(T_R) + mt + a\cos(\Omega t + \phi)$$

San Francisco Bay

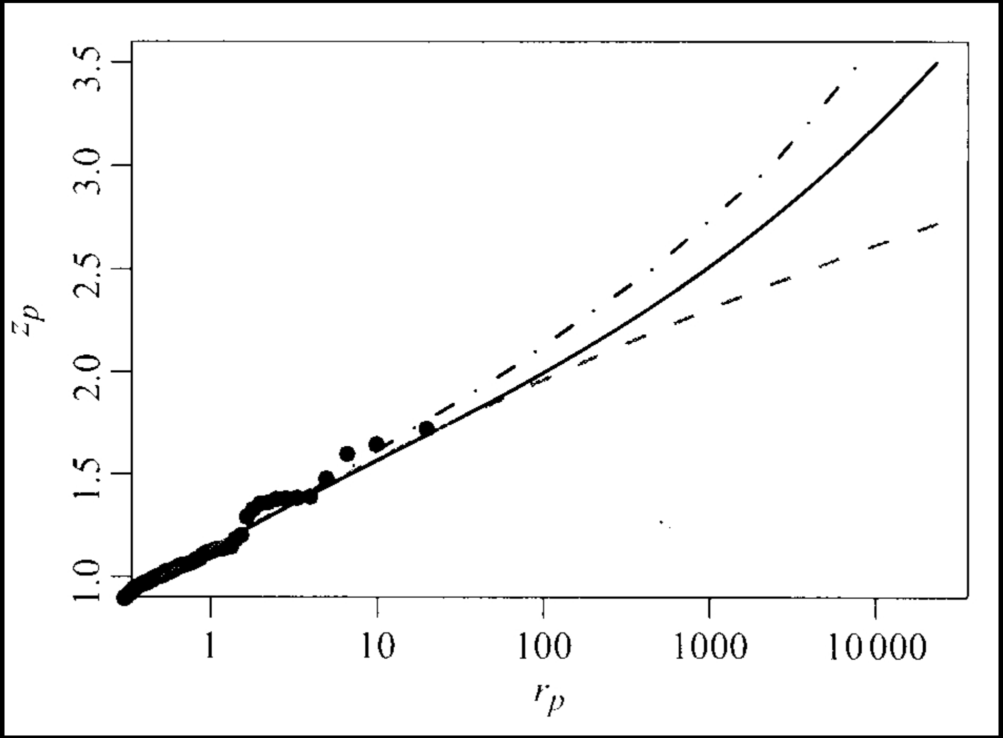


Sea Level

Joint probability method – combined surge and tide levels

Heffernan & Tawn (2004) conditional method for multivariate extremes – gives risk related to sea levels and wave heights

Coles & Tawn (2005) Bayesian framework aimed at spatial and seasonal analysis of extreme sea levels

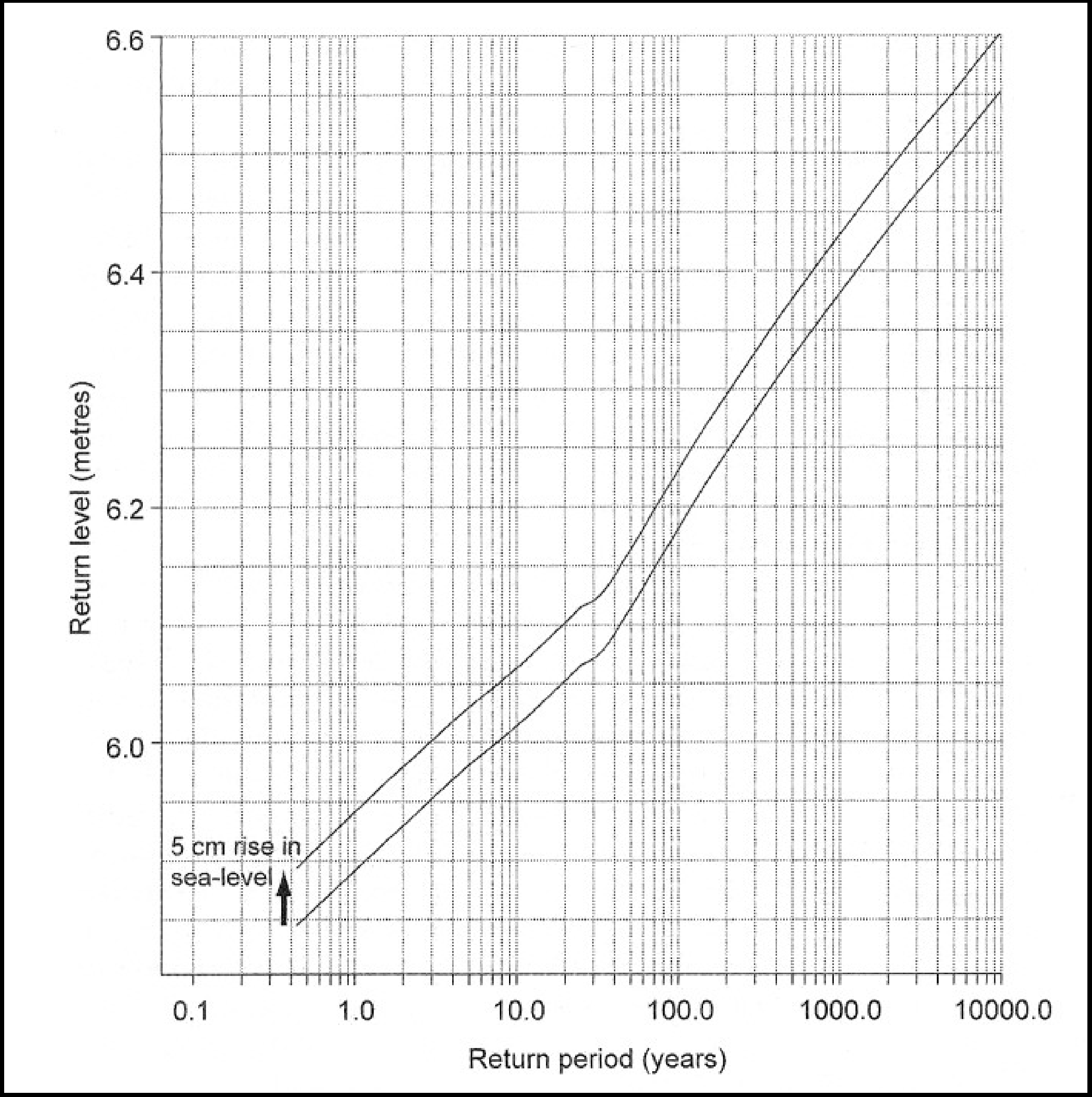


high tide surges v return period at Lowestoft

- dot-dashed curve = Bayesian + seasonal
- dashed = standard estimate
- solid = Bayesian predictive

Sea Level

Effect of sea level rise on extreme water levels: Newlyn



Dixon & Tawn, 2005

Sea Level

Moreover, a 30 cm rise in sea level causes 2/3 reduction in return period of a given sea level

10% change in return level due to climate variability can cause order of magnitude change to return period!

Holland, 1953

Image from Open University, UK

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Tsunami

Long waves due to abrupt mass displacements of water

Coastal vegetation can offer substantial frictional resistance

Hawaii, 1946

CERC, Shore Protection Manual

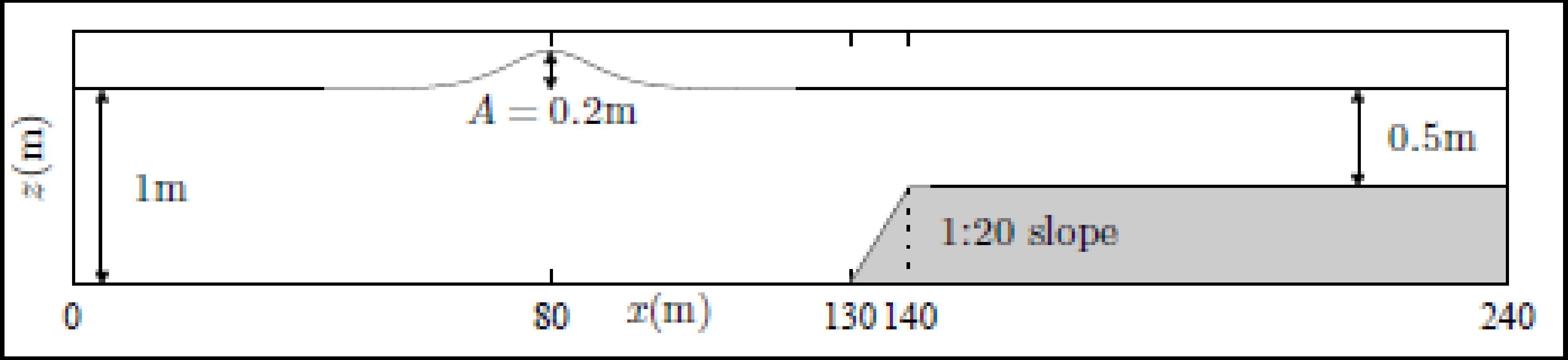
Lituya Bay, Alaska, 1958

December 2004 Indian Ocean tsunami → 225,000 fatalities

Tsunami, Japan, March 2011

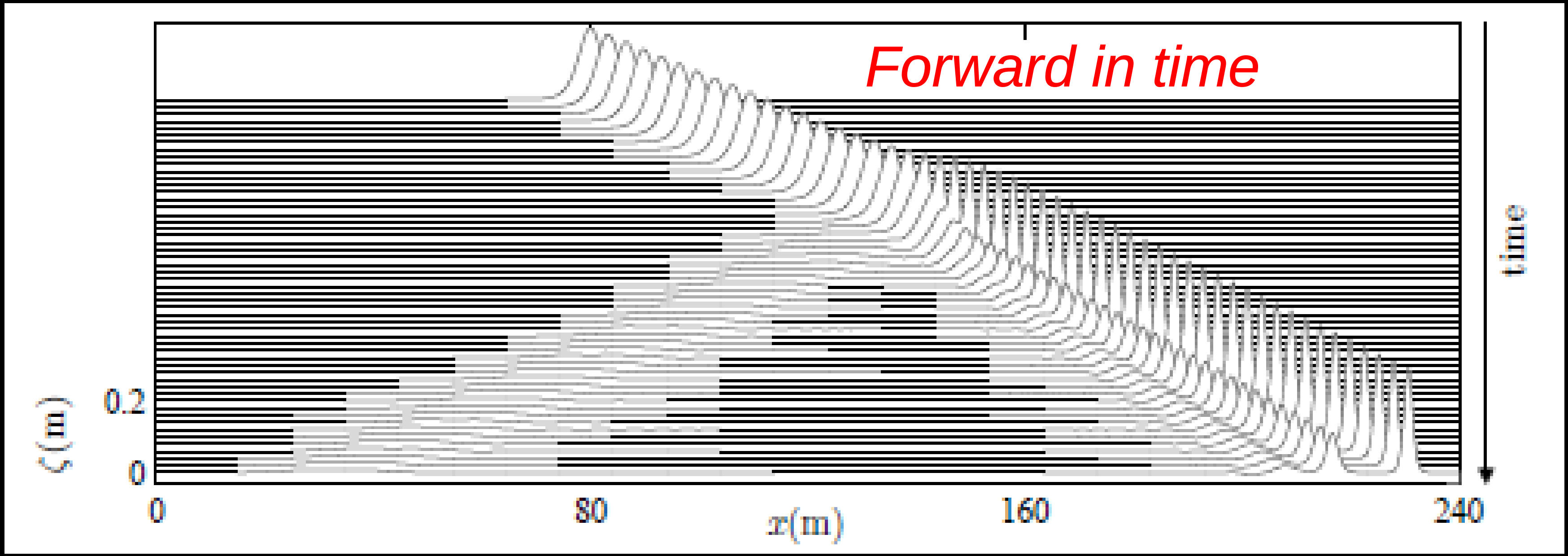
Associated Press

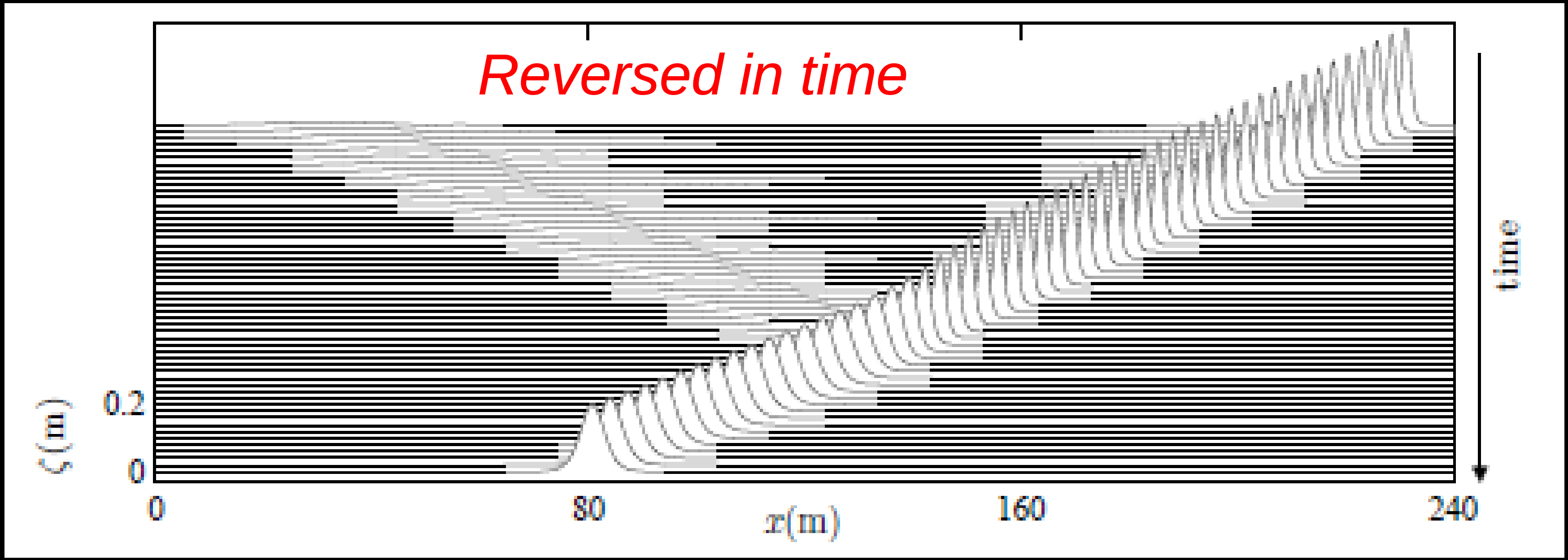
Verification – splitting of solitary wave over a shelf



Orszaghova (2011)

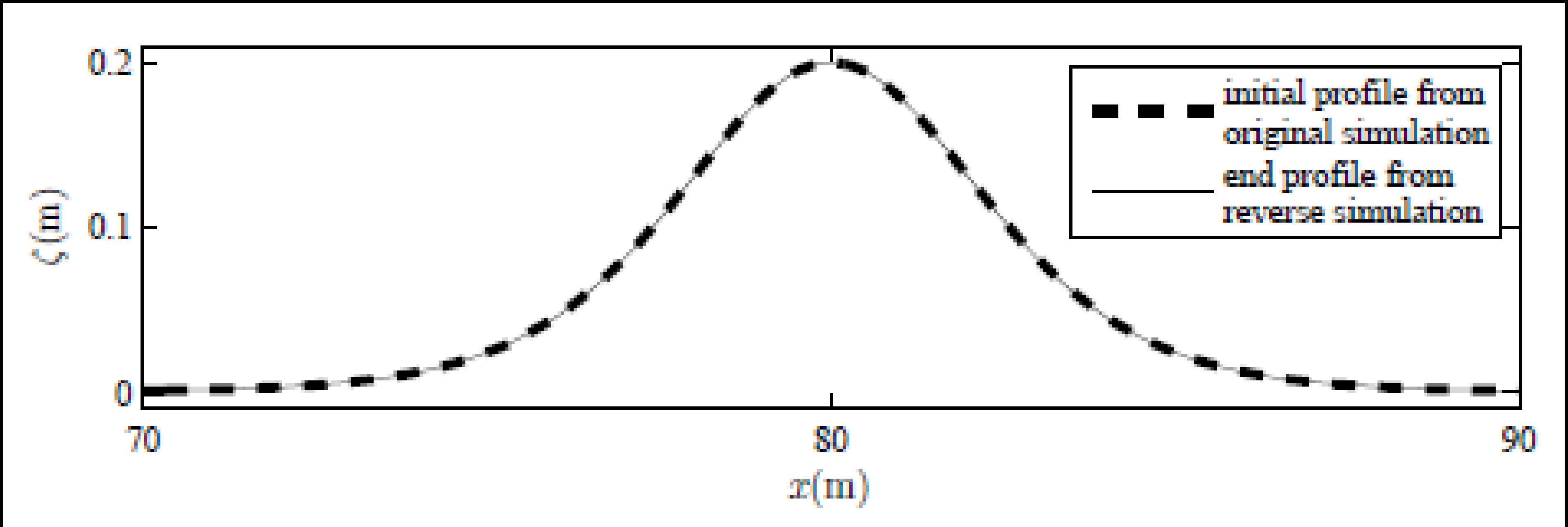
Verification – splitting of solitary wave over a shelf





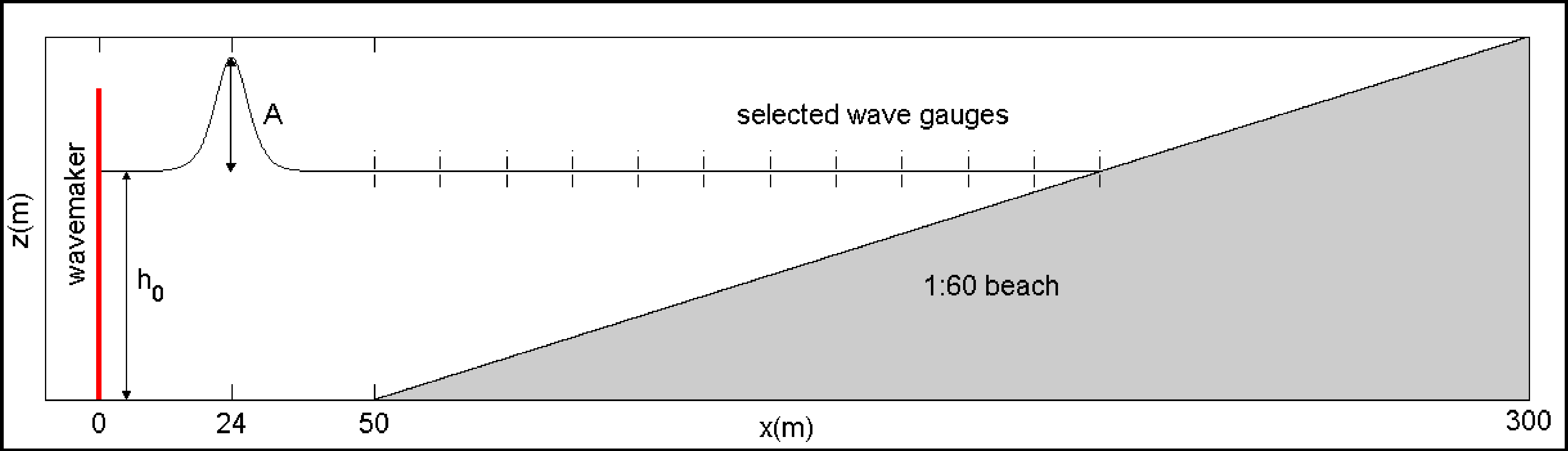
Orszaghova (2011)

Verification – wave splitting reversibility check



Orszaghova (2011)

Tainan Supertank: solitary wave run-up at a plane beach

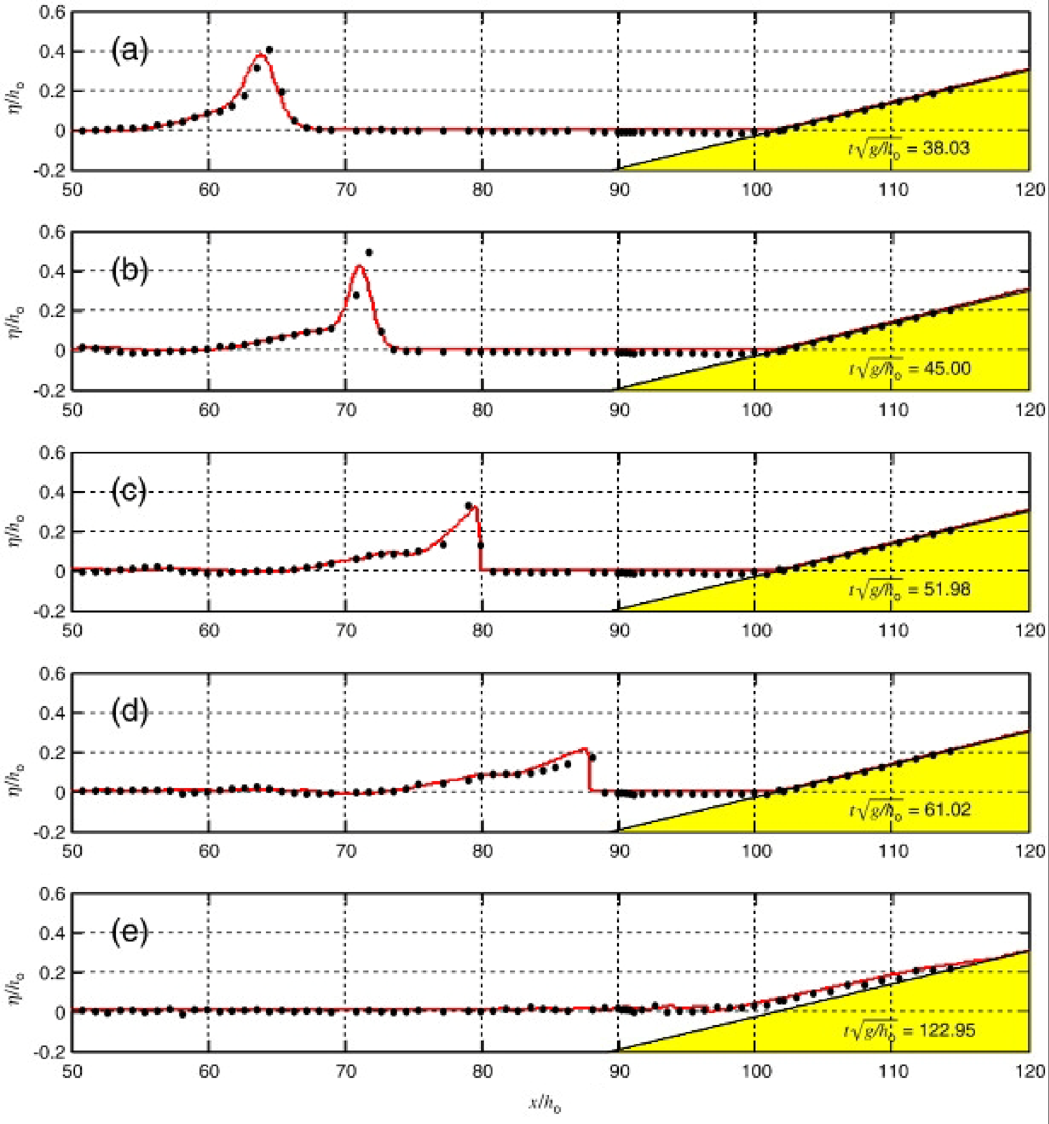


Tank: length 300 m, width 5 m, depth 5.2 m

Measurements by Hsiao *et al.* (2008)

Numerical modelling by Orszaghova *et al*. (2011)

Solitary wave in Tainan Supertank

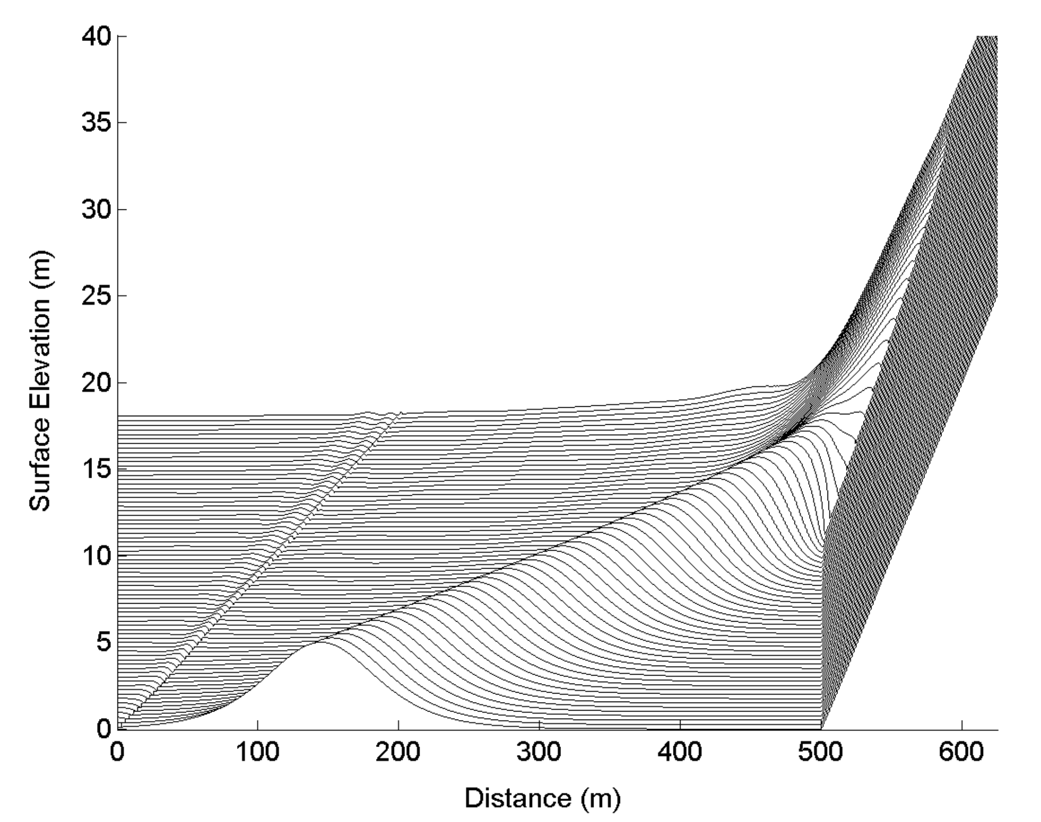


Experimental data: Hsiao et al. (2008); Numerical: Orszaghova *et al*. (2012)

Tsunami

10 cm amp solitary wave in UKCRF → ~ 5 m horizontal inundation

For 2 m prototype tsunami → inundation of 100s of m



Simulation of idealised tsunami in eastern Kamchatka

run-up = 17.7 m

Borthwick, Ford, Weston, Taylor & Stansby 2006

Advances in tsunami simulation

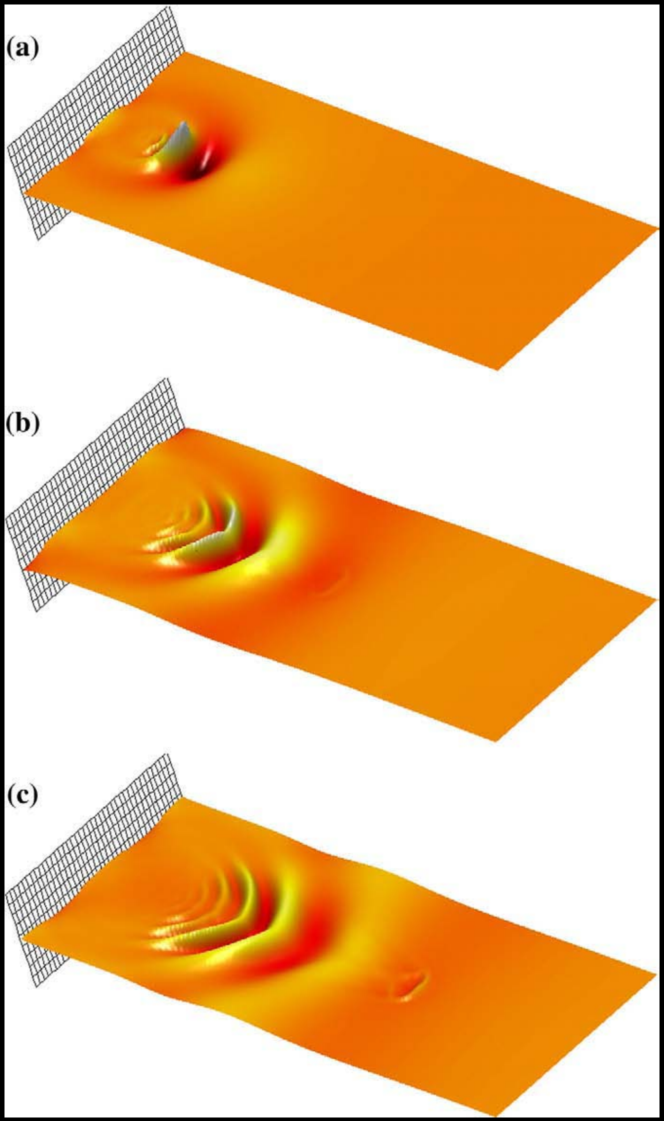
High order Boussinesq
(Fuhrman & Madsen, 2009)

Potential flow (e.g. Grilli & Watts 2005)

SPH (e.g. Rogers & Dalrymple 2006)

RANS (e.g. Lin, Chang & Liu 1999)

Submarine-induced tsunami



Fuhrman & Madsen, 2009

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Storm driven waves on the Cornish Coast 1990

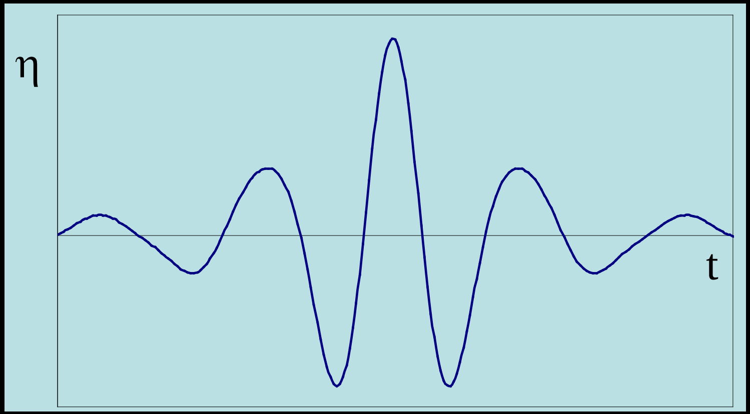
Extreme Storm-induced Waves

Usually modelled using regular and random wave tests – but …

regular waves not representative of extreme waves

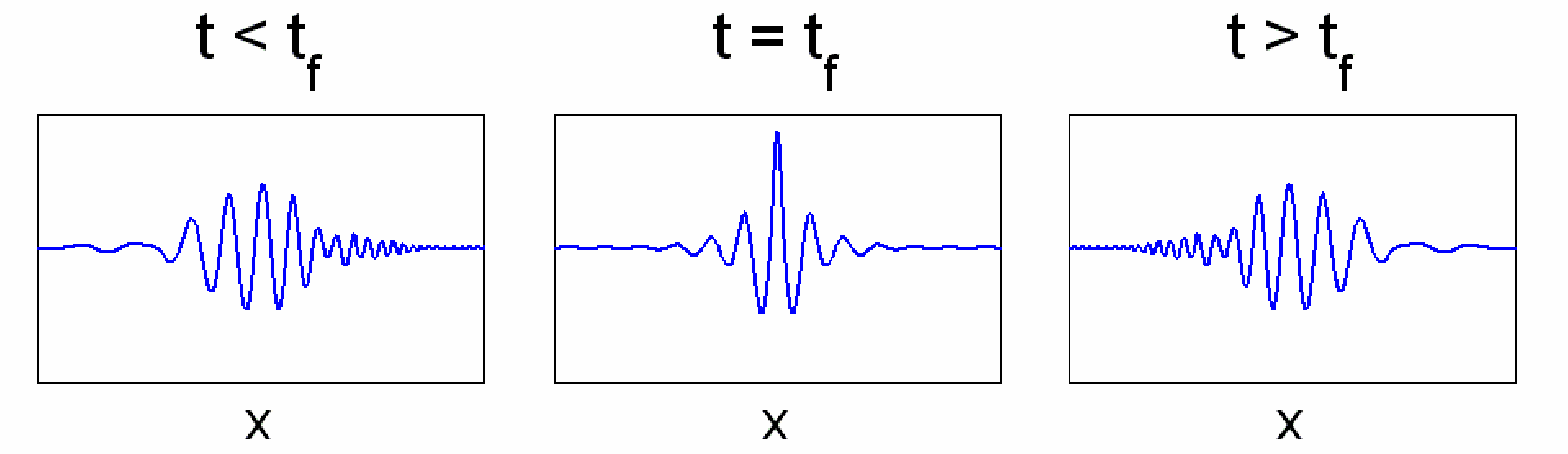
random wave tests time-consuming and contaminated by long wave reflections

NewWave focused wave group – shape fits the average profile of the extreme event in a given spectrum



Focused wave group

$$\eta(x,t) = \sum_{n=1}^{n=N} a_n \cos(k_n(x - x_f) - \omega_n(t - t_f))$$



- no reflections
- linear theory for paddle signal

U.K. Coastal Research Facility

27 m cross-shore

36 m alongshore

72 wave paddles

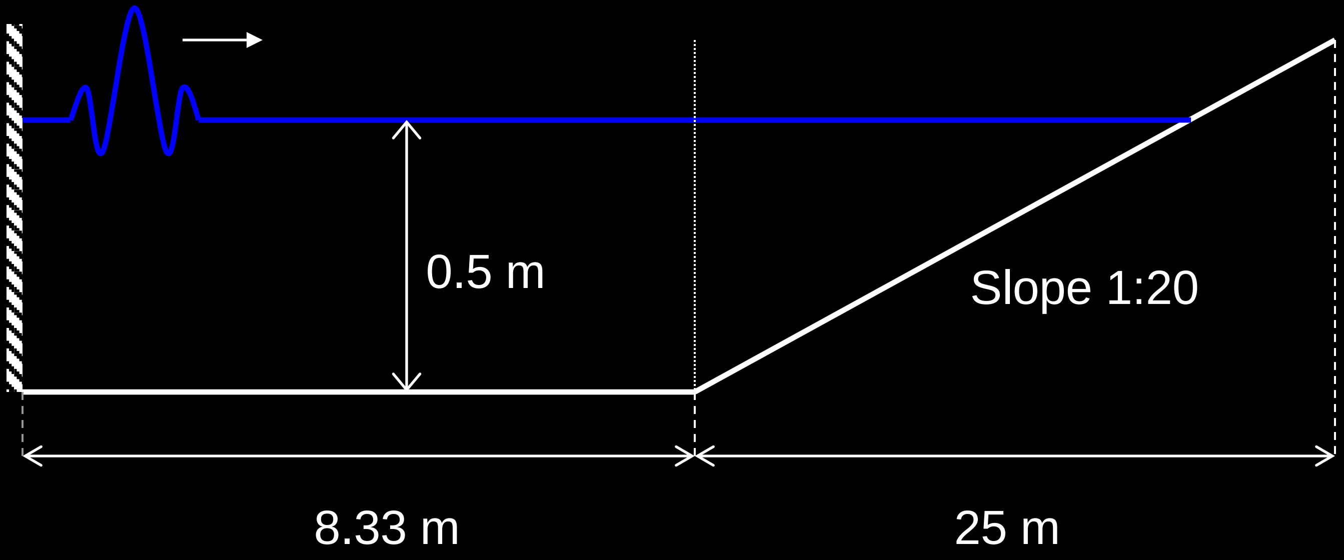
0.5 m water depth

1:20 plane beach

- surface elevation + run-up on beach
- kinematics with LDA+ADV
- also with sloping sea-wall, overtopping

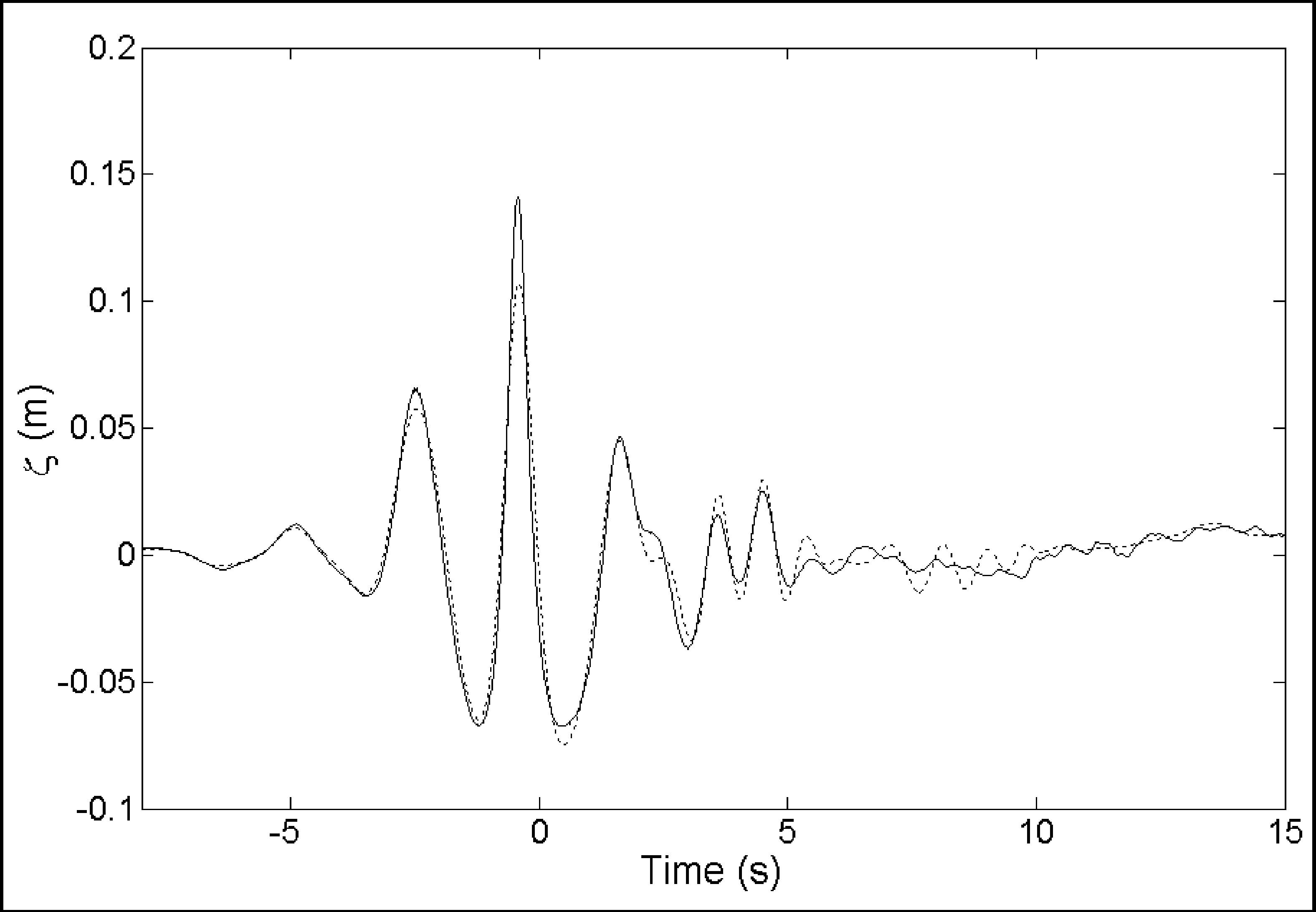
Focused Wave Groups in UKCRF

Group amplitude = 0.114 m



1-D UKCRF Crest-focused Wave Group

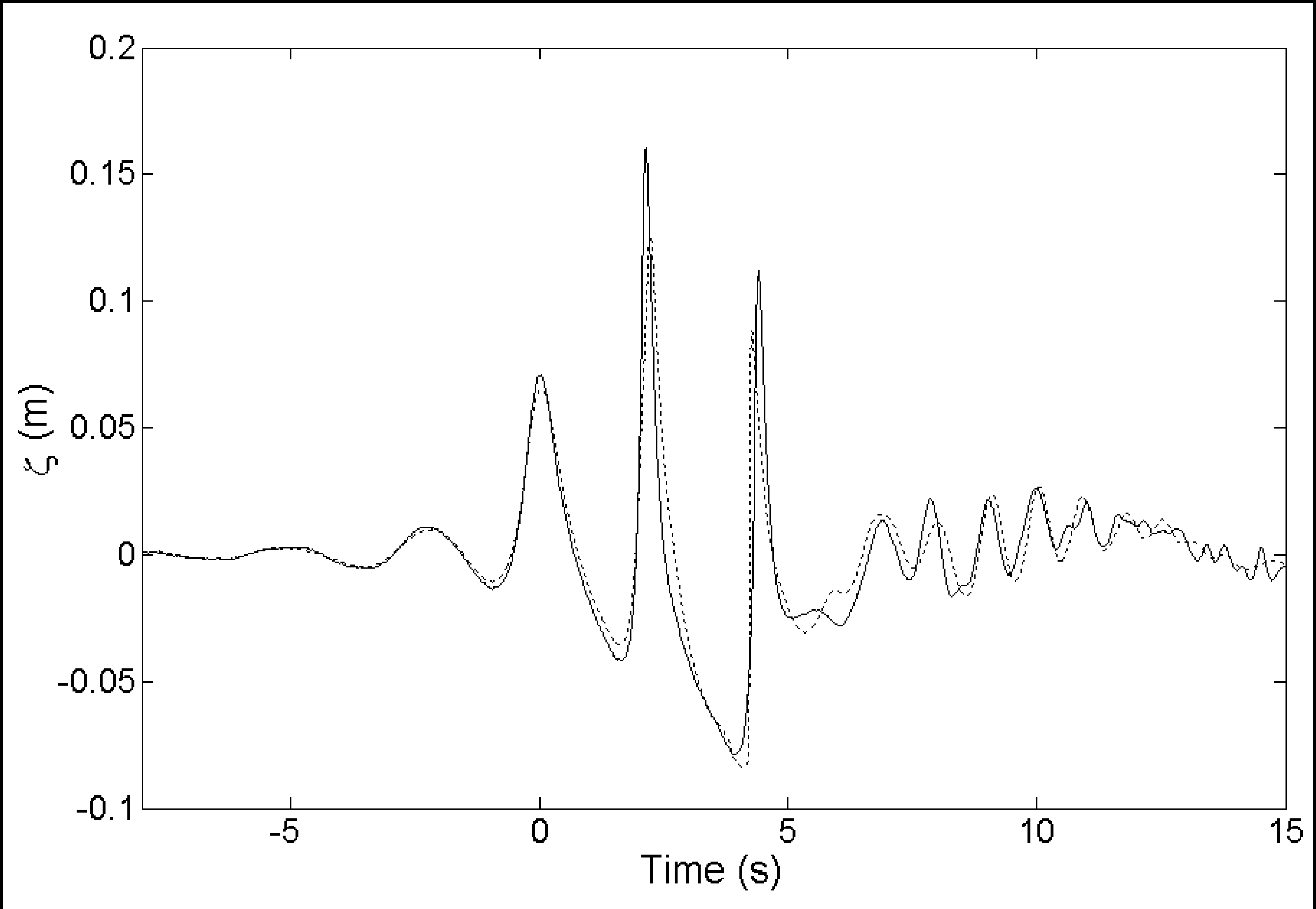
beach toe



Weston, Borthwick, Taylor & Hunt 2005

1-D UKCRF Crest-focused Wave Group

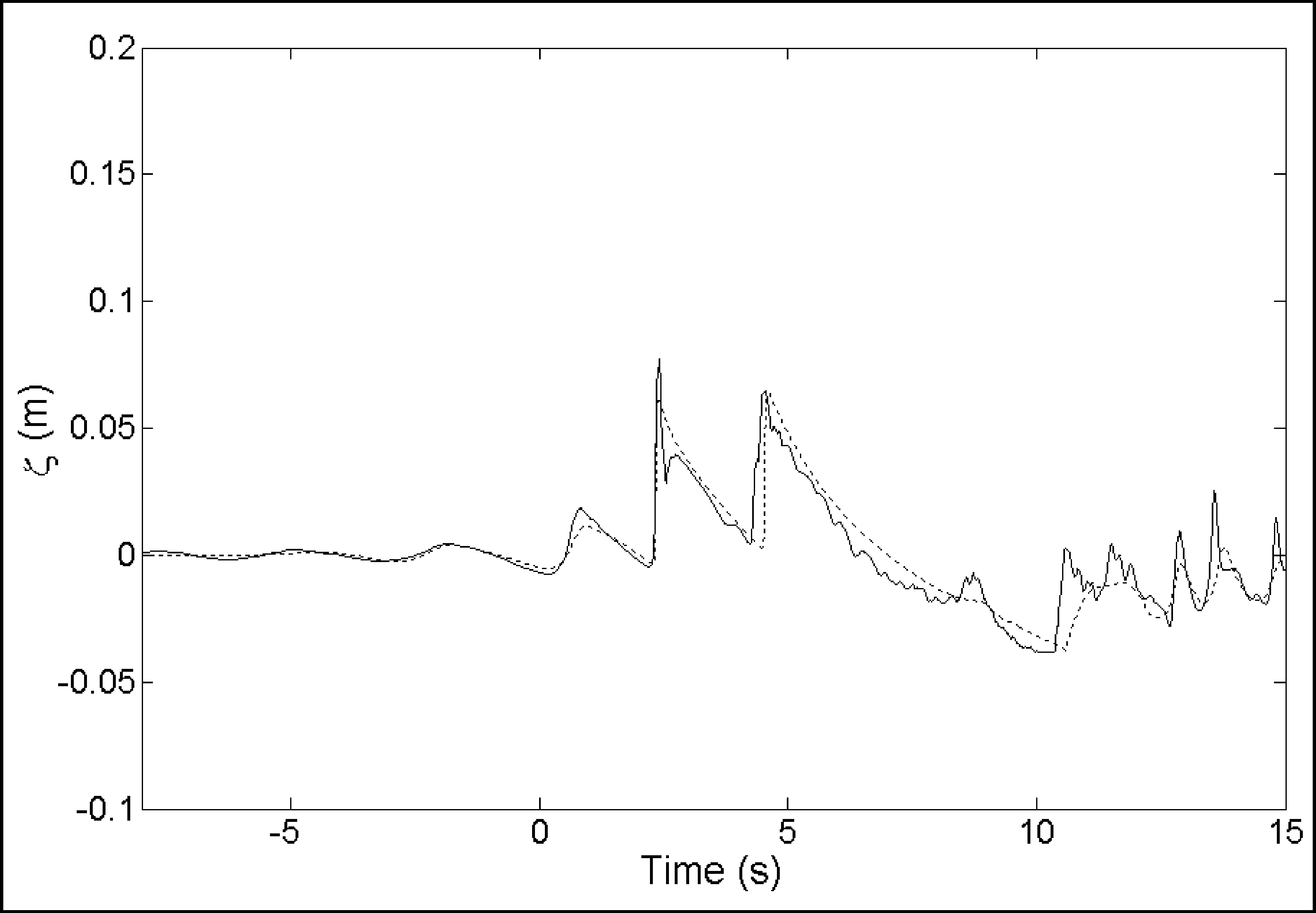
5 m after beach toe



Weston, Borthwick, Taylor & Hunt 2005

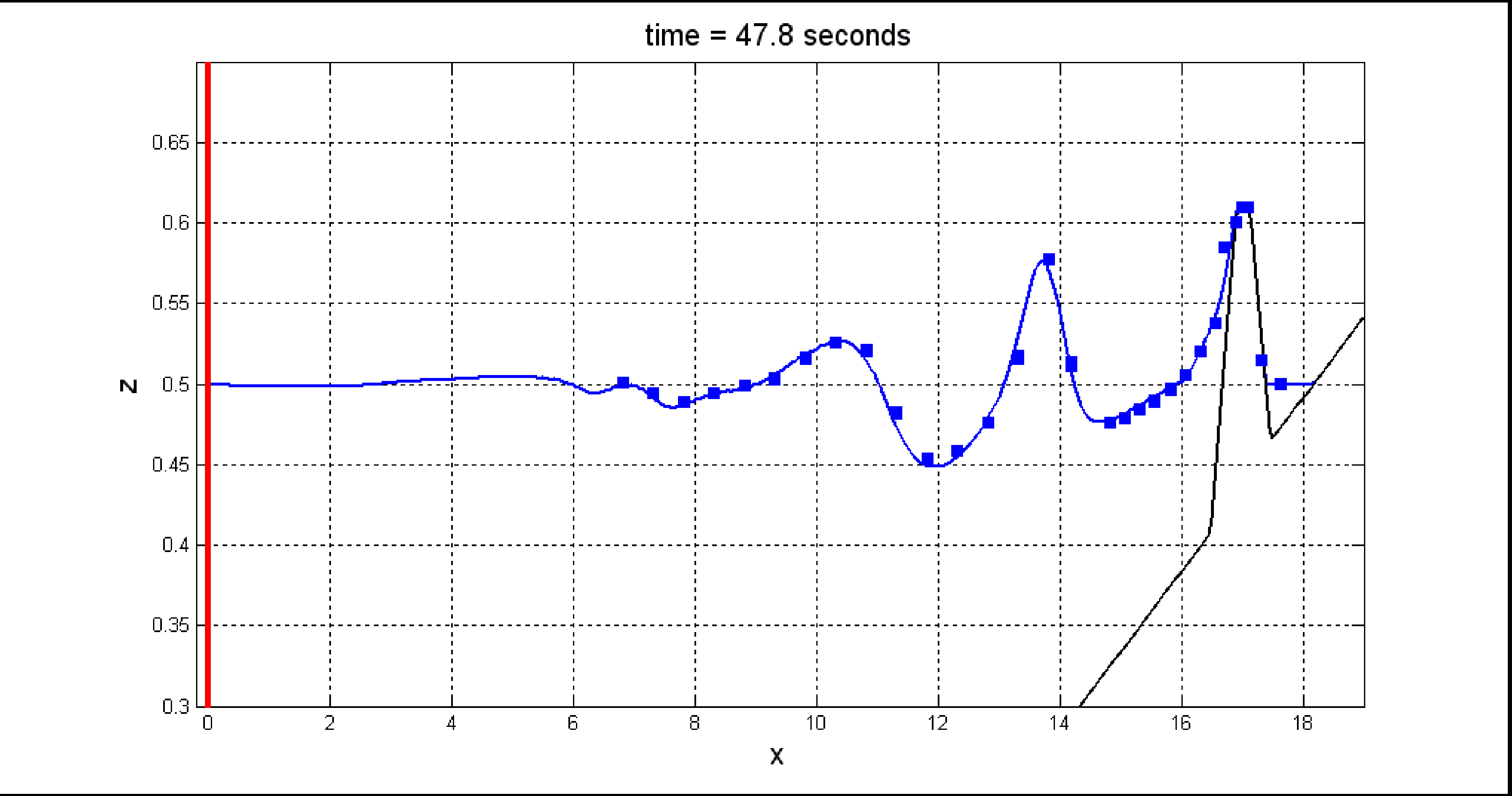
1-D UKCRF Crest-focused Wave Group

9 m after beach toe



Weston, Borthwick, Taylor & Hunt 2005

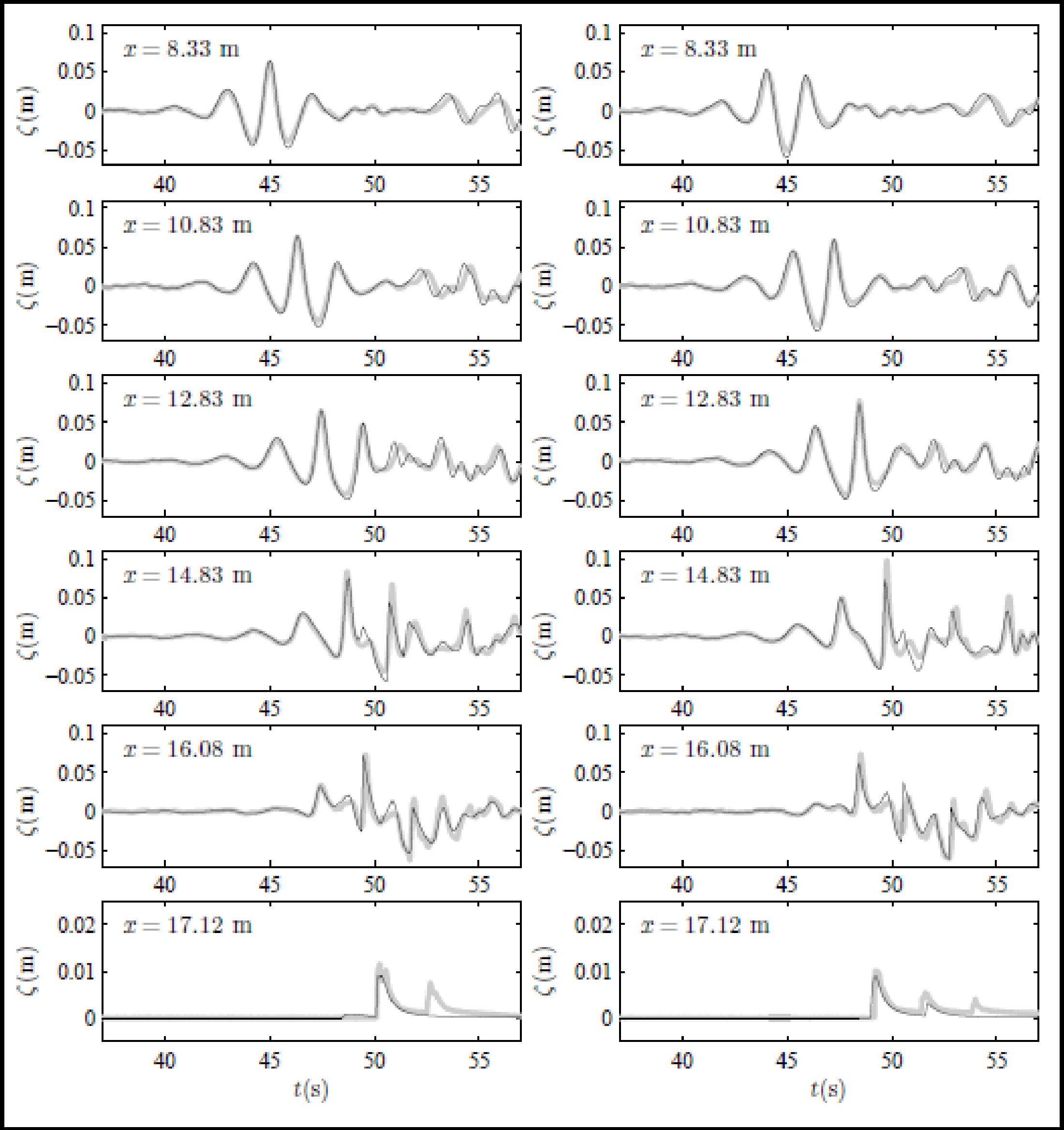
Focused wave group interacting with seawall in UKCRF



UKCRF data: Hunt *et al*. (2004) Numerical model: Orszaghova *et al.* (2012)

Focused wave group overtopping a seawall in the UKCRF

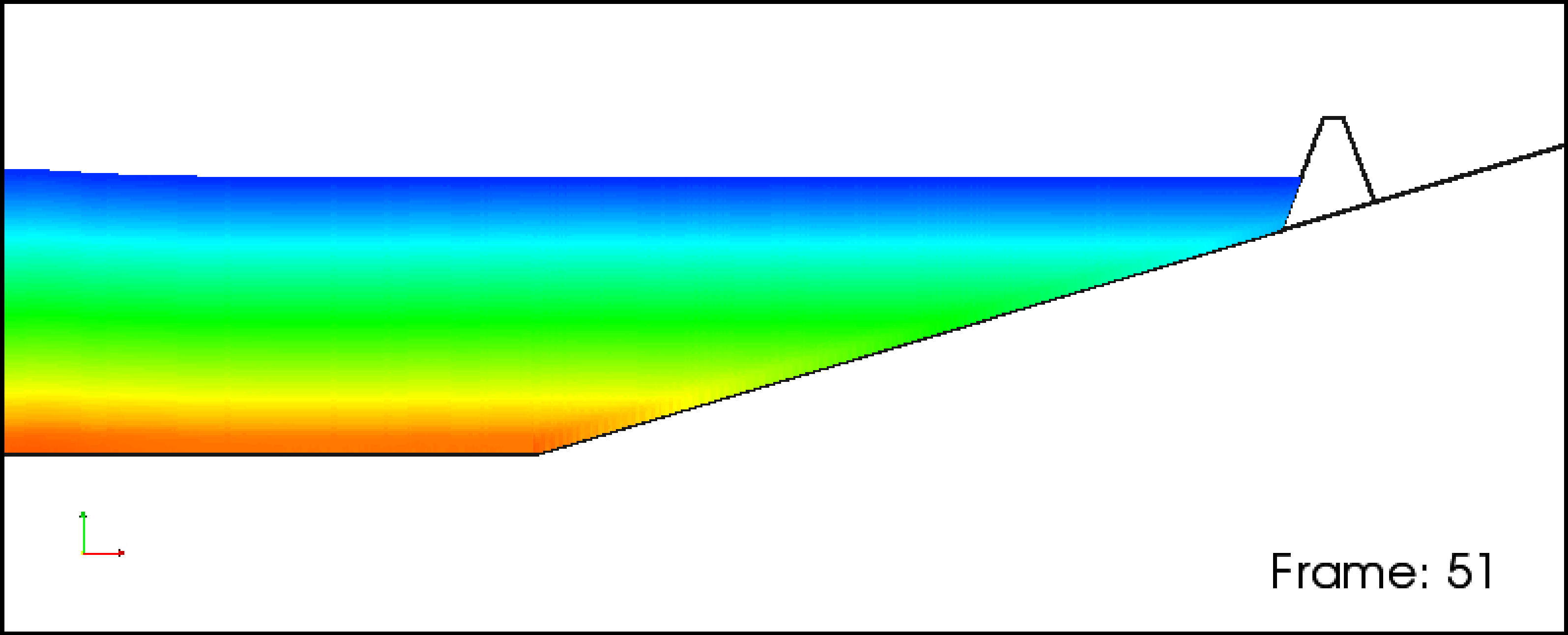
Crest-focused



Trough-focused

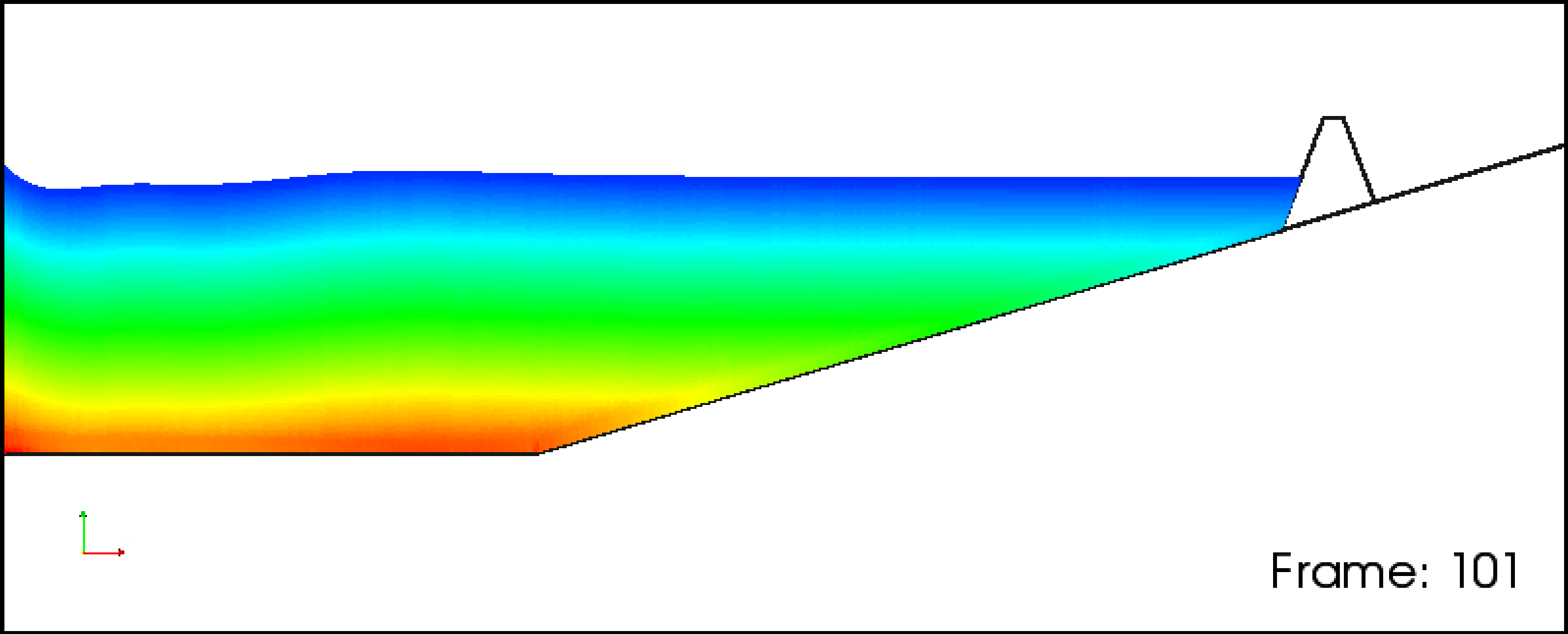
UKCRF data: Hunt *et al*. (2004) Numerical model: Orszaghova *et al.* (2012)

SPH simulation of focused wave overtopping



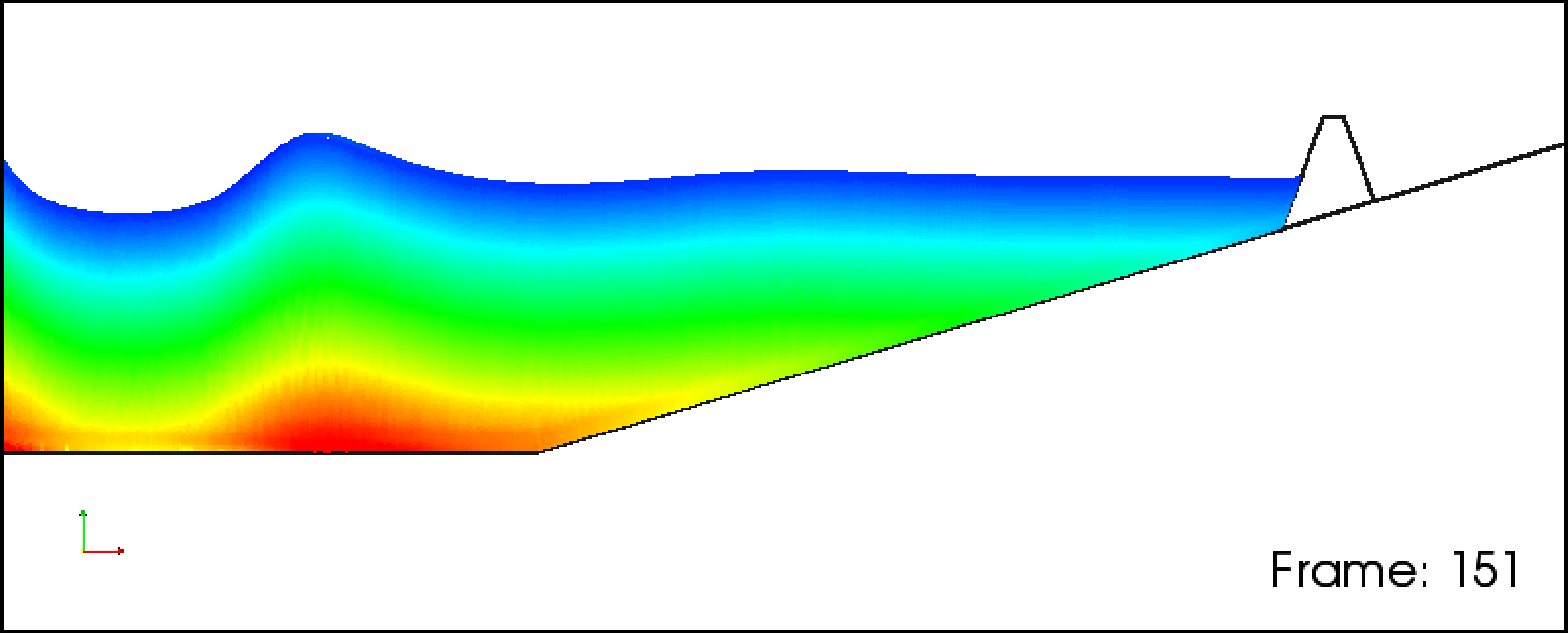
Rogers, 2009

SPH simulation of focused wave overtopping



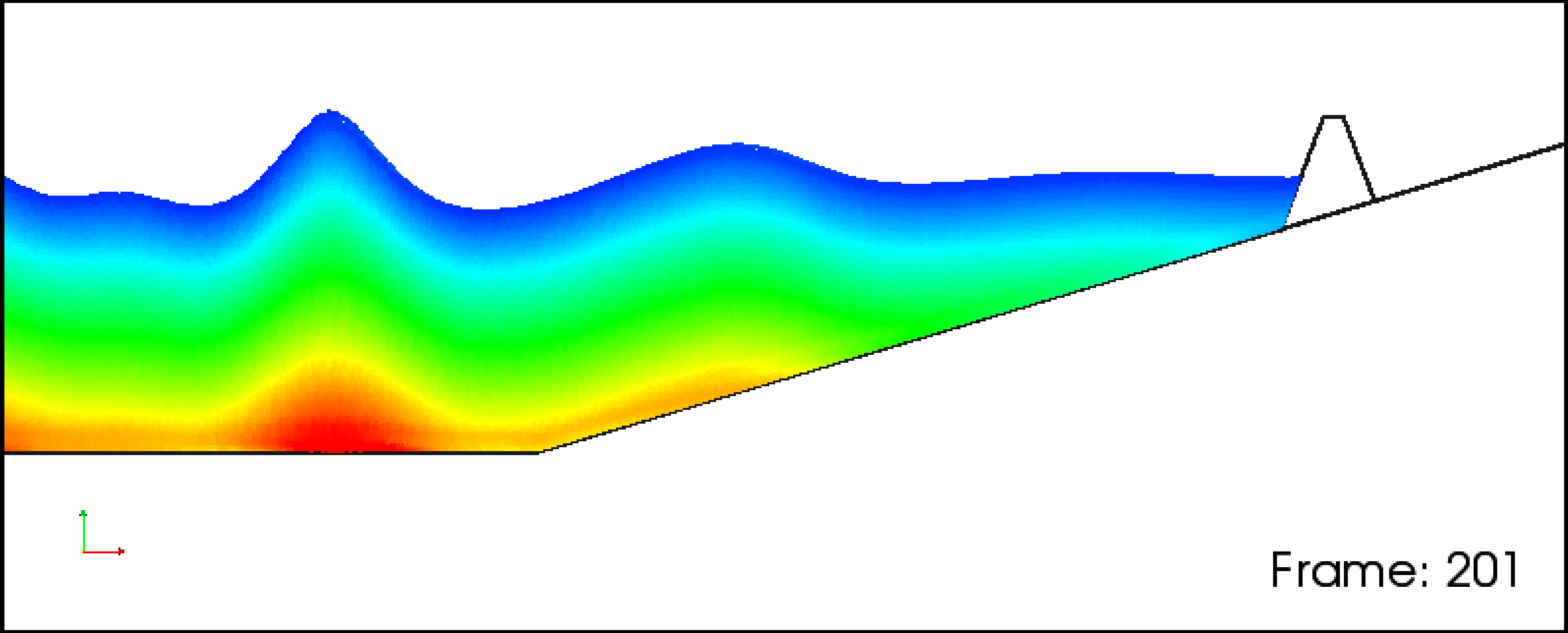
Rogers, 2009

SPH simulation of focused wave overtopping



Rogers, 2009

SPH simulation of focused wave overtopping



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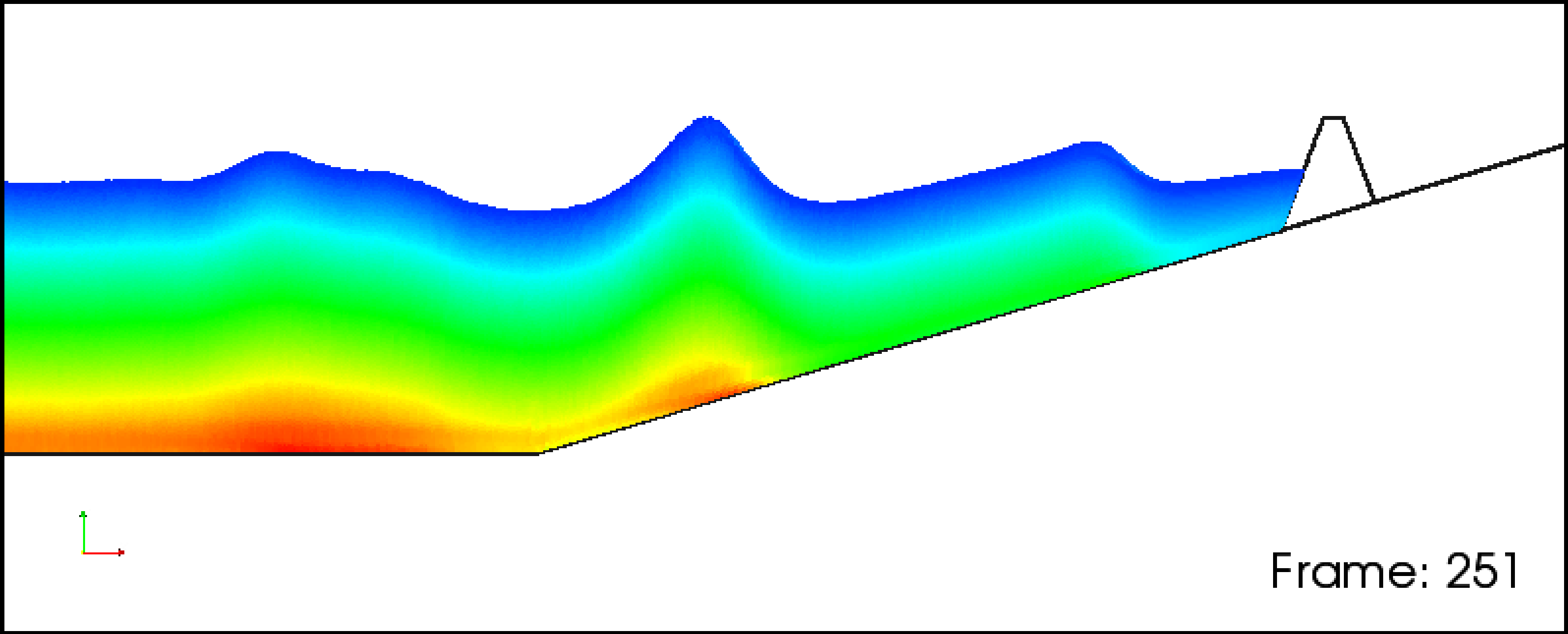

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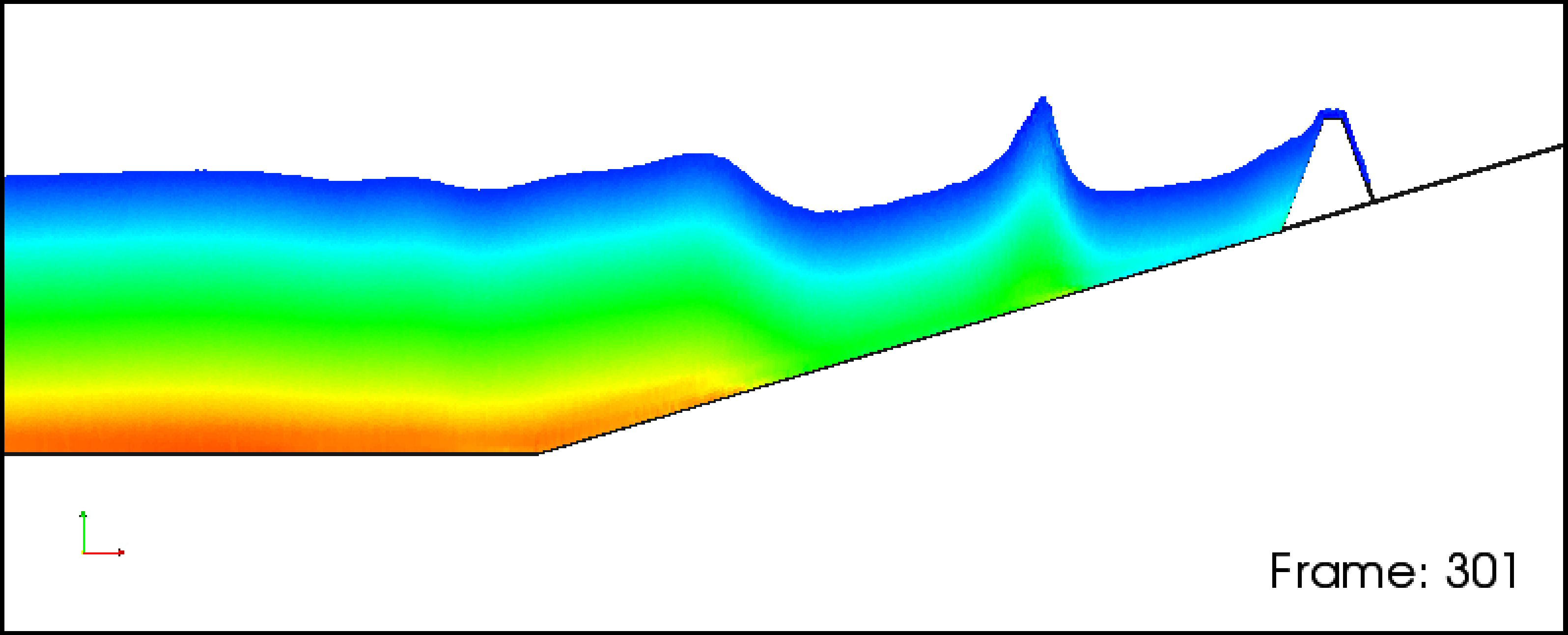
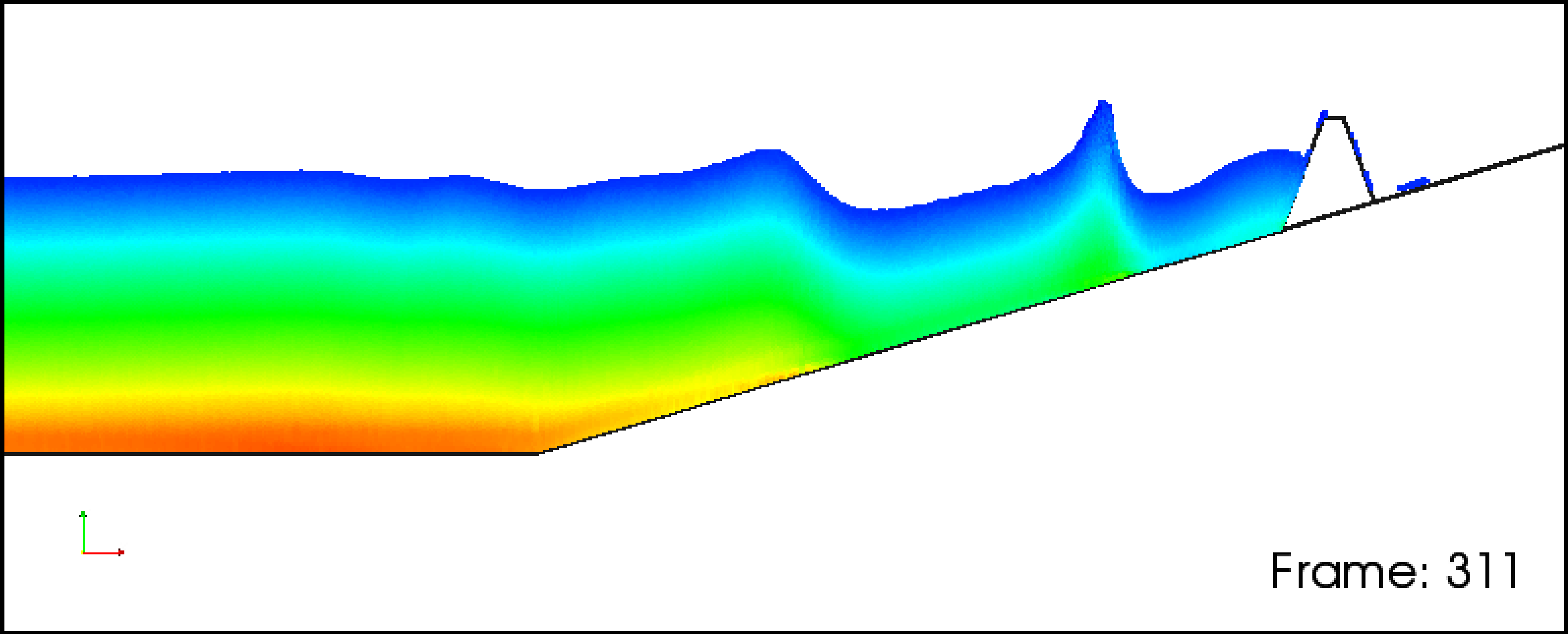


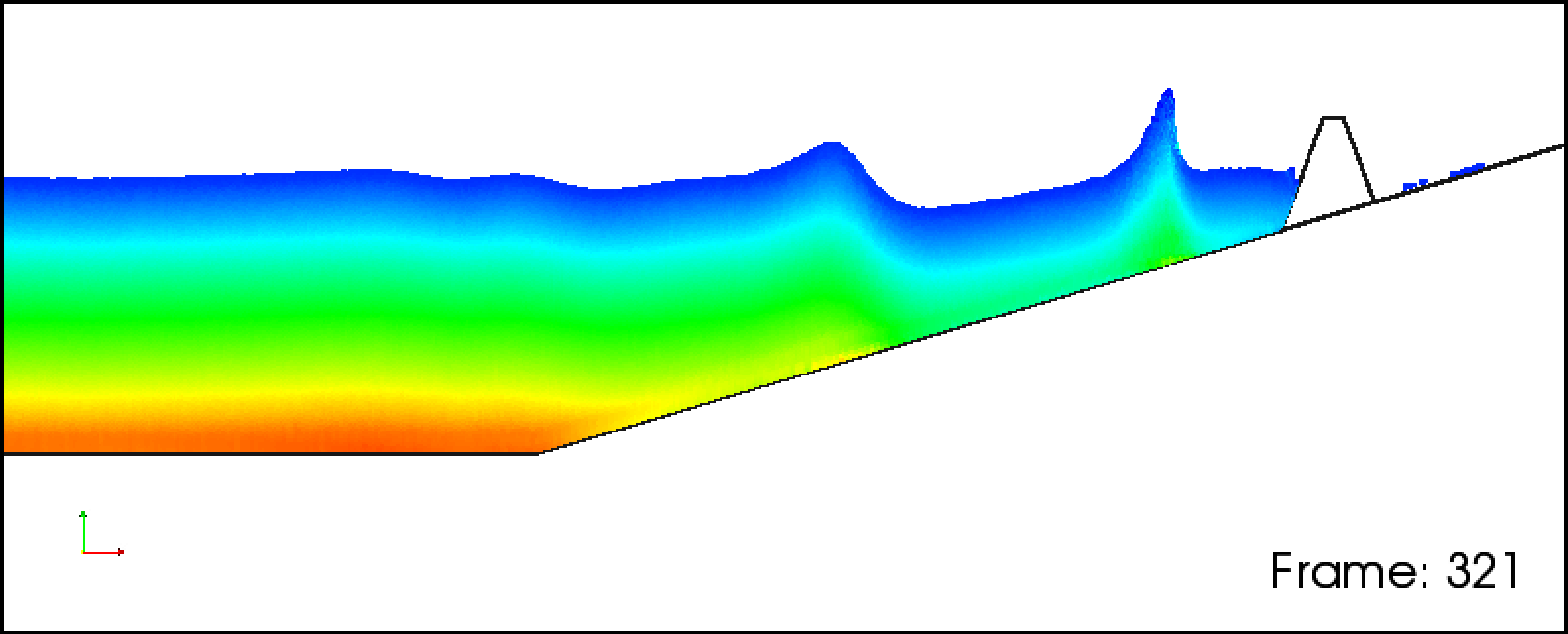
Rogers, 2009

SPH simulation of focused wave overtopping



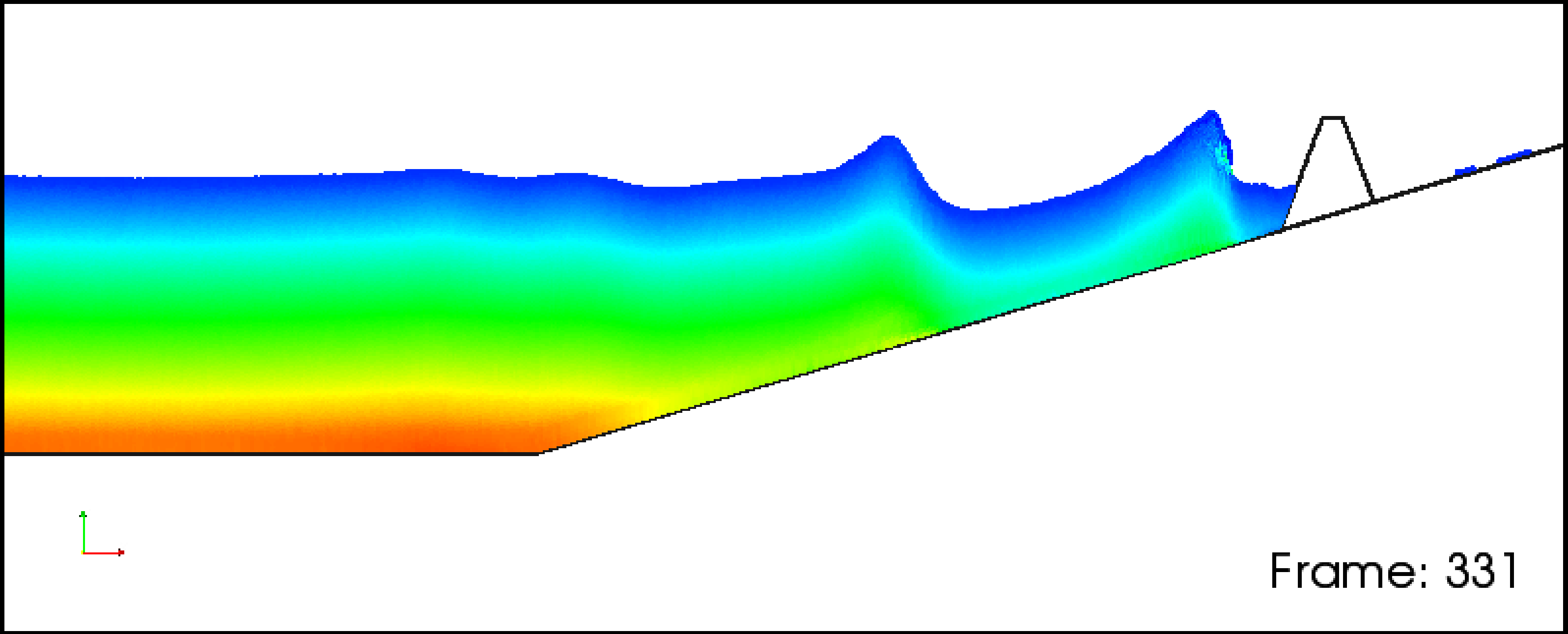
Rogers, 2009

SPH simulation of focused wave overtopping



Rogers, 2009

SPH simulation of focused wave overtopping



Rogers, 2009

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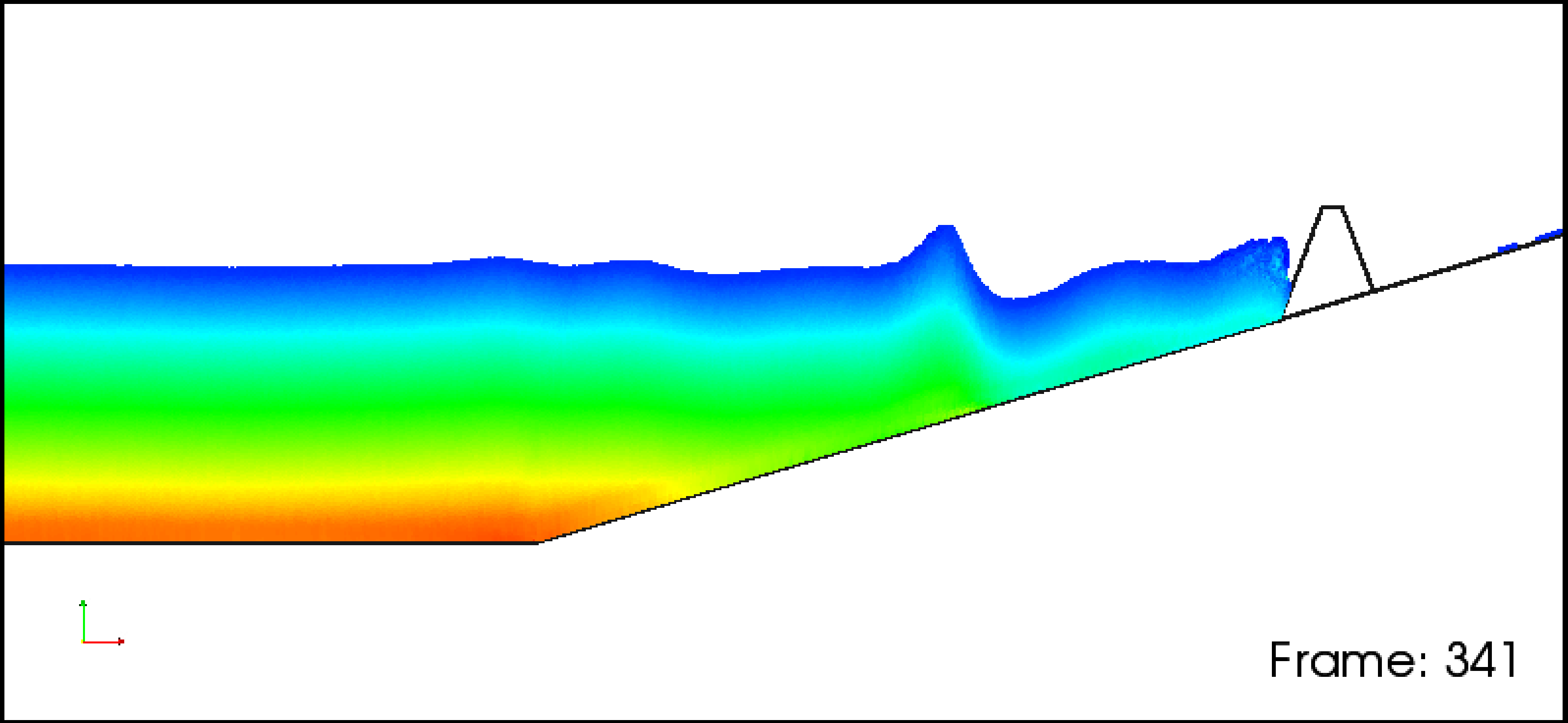

Rogers, 2009

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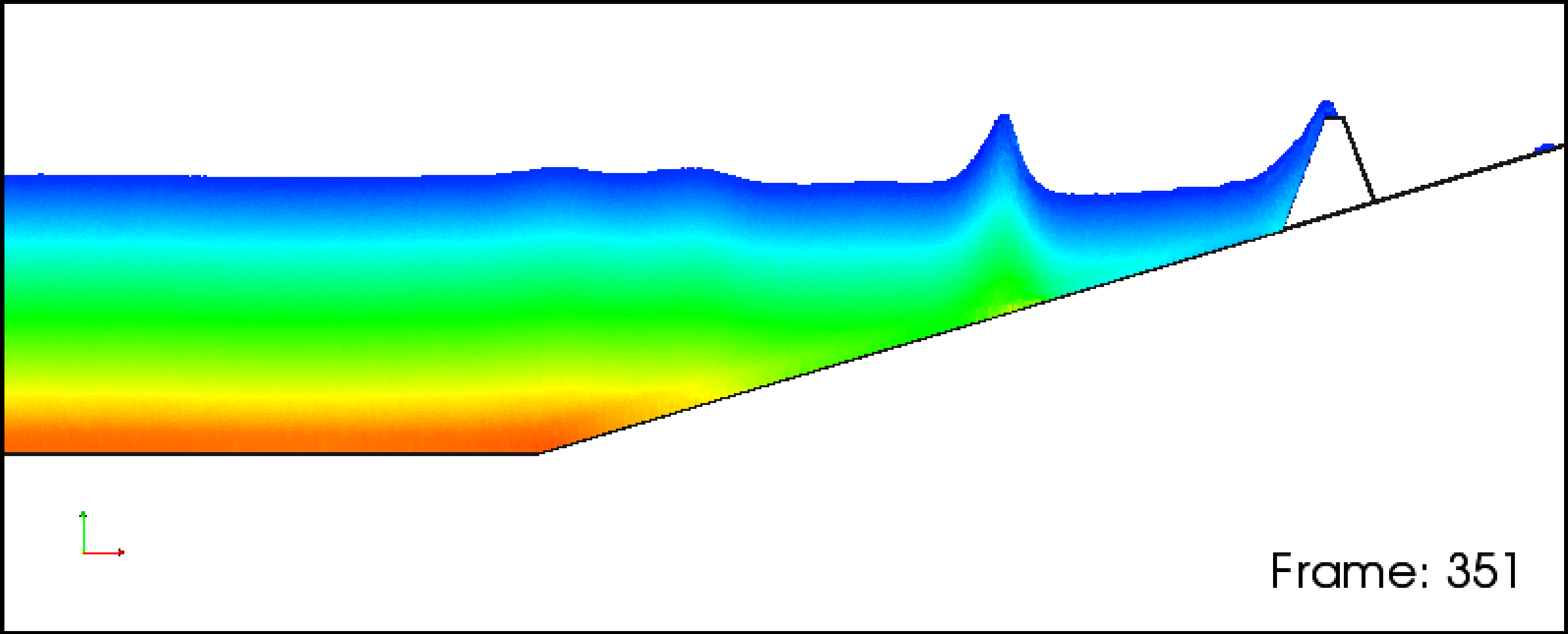
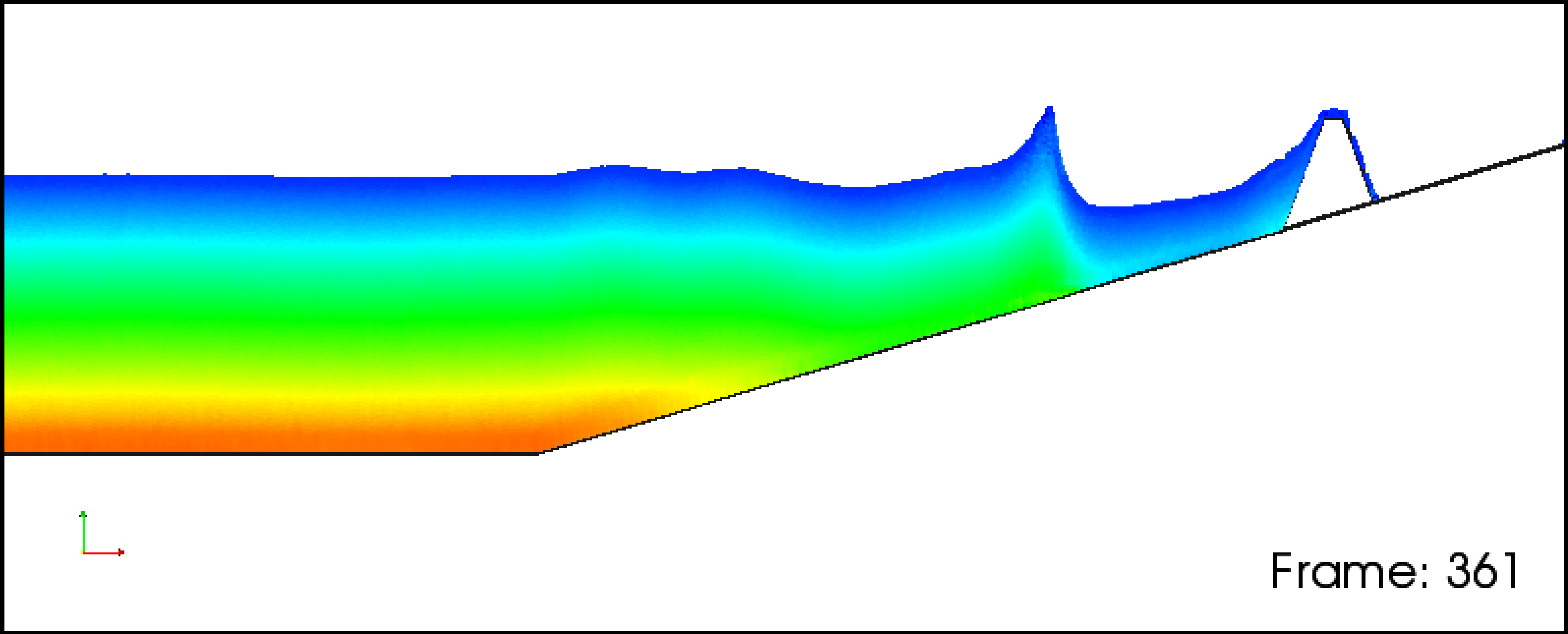


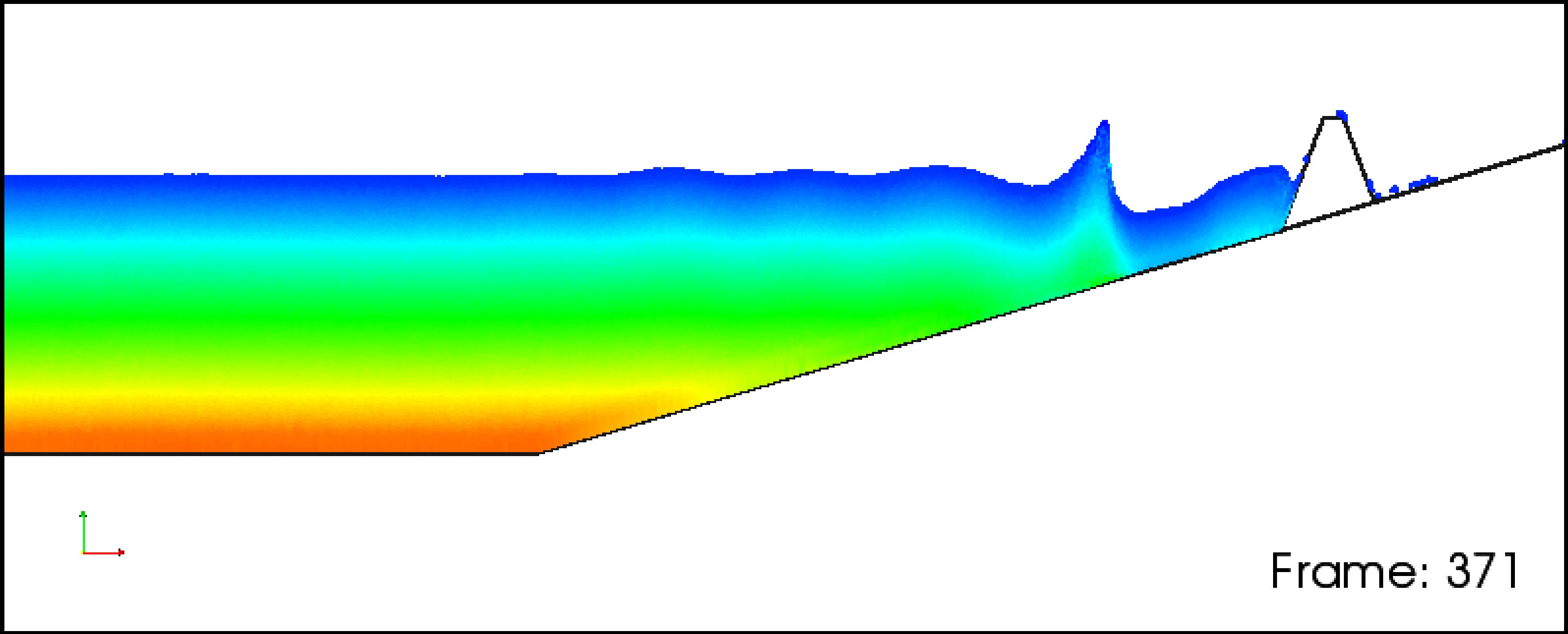
Rogers, 2009

SPH simulation of focused wave overtopping



Rogers, 2009

SPH Simulation of focused wave overtopping

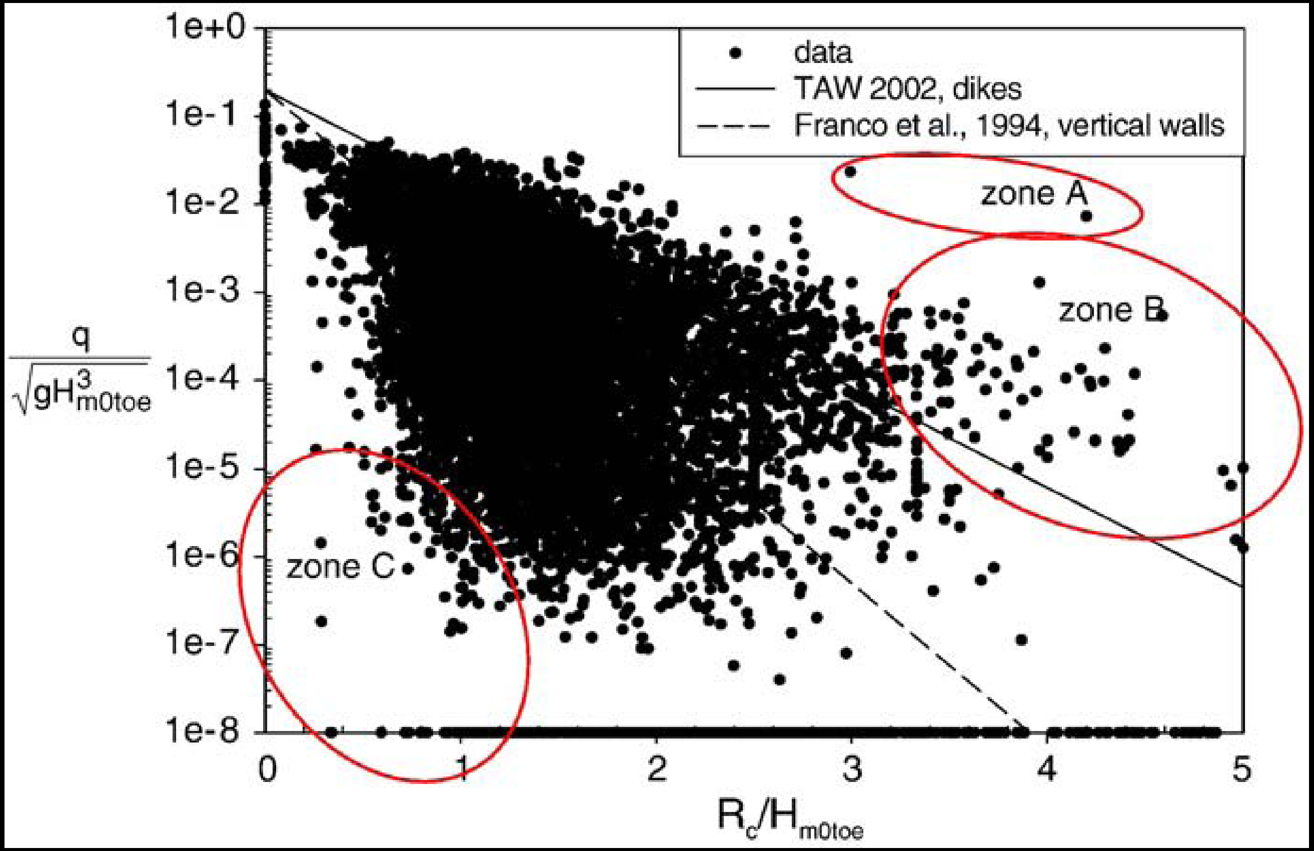


Rogers, 2009

Advanced empirical methods for wave run-up and mean overtopping discharges for coastal structures

van der Meer, Verhaeghe, & Steendam (2009): data from > 10,000 wave tests

dimensionless overtopping discharge



dimensionless crest freeboard

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Coastal flood risk strongly impacted by breaching of dunes and embankments

Flow discharge and velocity through a breach as it grows are particularly important

Failure is through bank erosion, slope instability, and piping mechanisms

Breach Formation (IMPACT Project Field Tests)

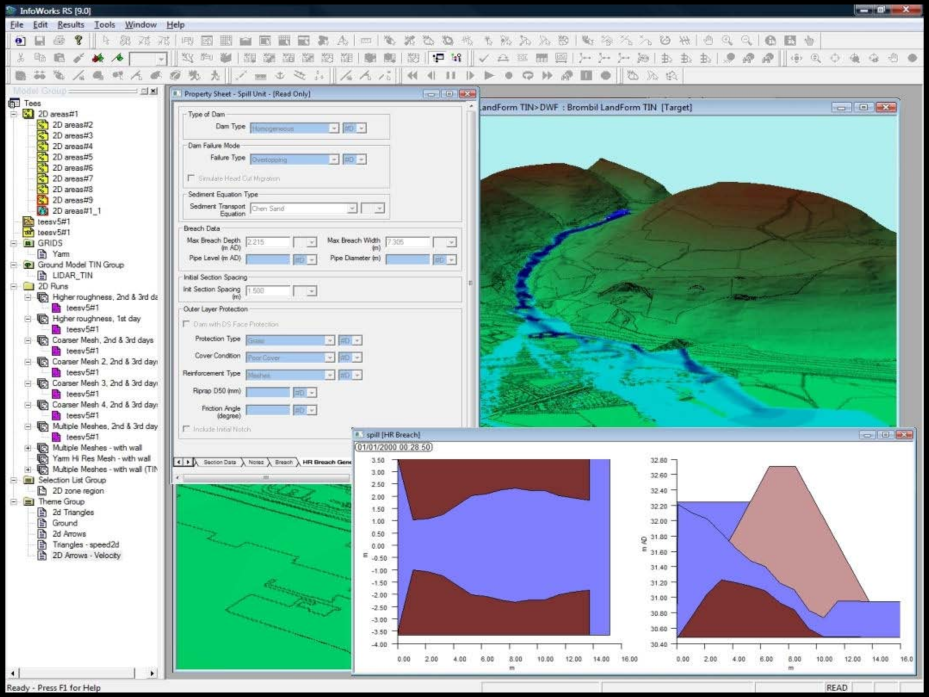
Non-cohesive material

Cohesive material

Morris, Hanson & Hassan 2008

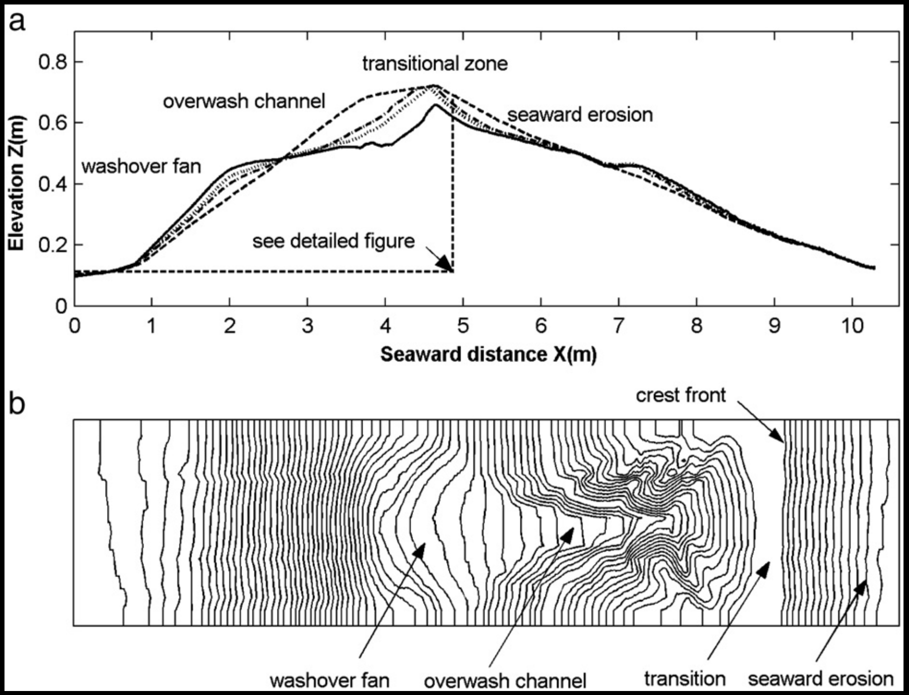
Integrated Breach Modelling

HR-BREACH



HR Wallingford 2008

Delft: process-based model



Tuan, Stive, Verhagen & Visser 2008

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Coastal Flood Inundation

Indicative Floodplain Maps based on GIS → information on coastal flood inundation extent for event of given T_R

Future Flooding Report examines effect on coastal flooding of sea level changes, using zonation maps indicating damage for different socio-economic scenarios:

World markets (high CO_2 emissions)

National enterprise (medium-high CO_2 emissions)

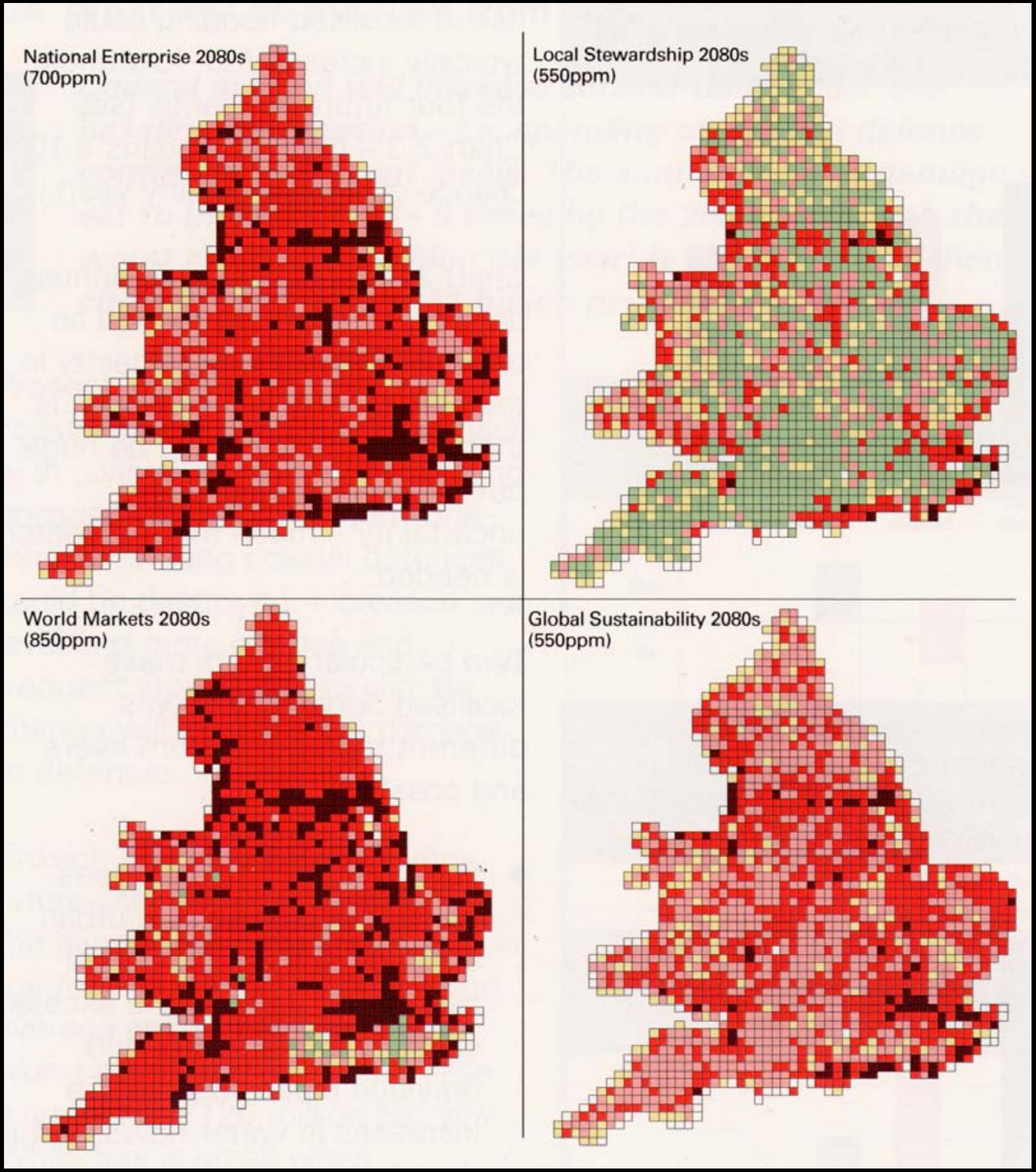
Local stewardship (medium-low CO_2 emissions)

Global sustainability (low CO_2 emissions)

Evans, Ashley, Hall, Penning-Rowsell, Saul, Sayers, Thorne, & Watkinson 2008

Flood Risk

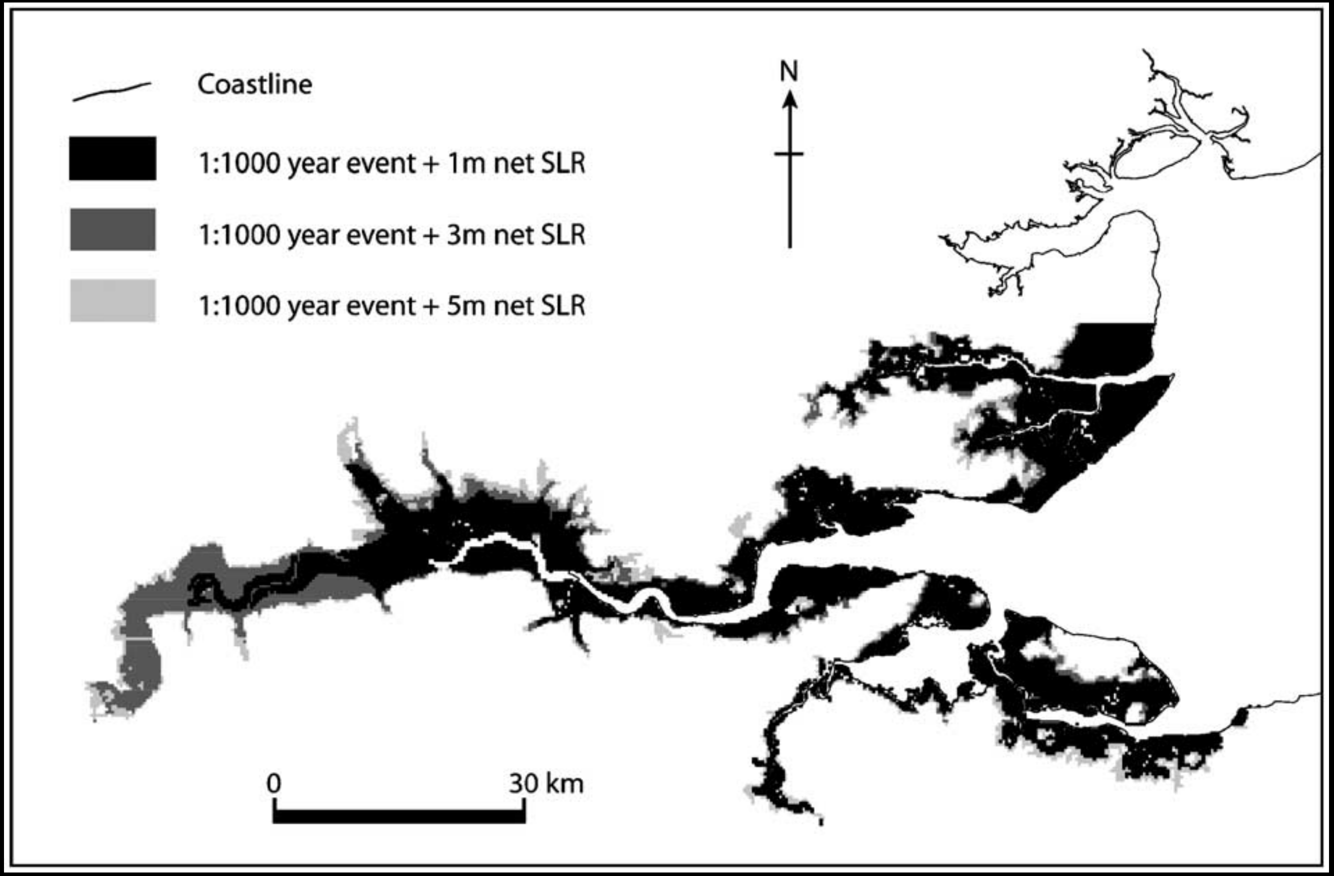
Average annual flood damage in 2080s



OST 2002

Coastal Flood Inundation

Sensible approach: fit probability distribution to mean sea level rise predictions from IPCC and use Monte Carlo simulations → flood probability maps, which can be combined with land values to estimate coastal flood risk



1 in 1000 year flood outline of Thames estuary

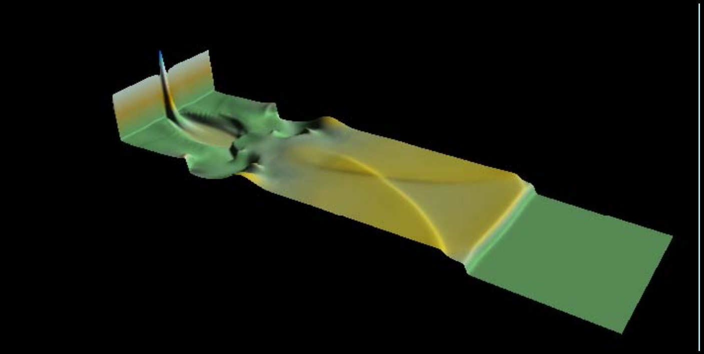
Bates, Dawson, Hall, Horritt, Nicholls, Wicks & Hassan 2005

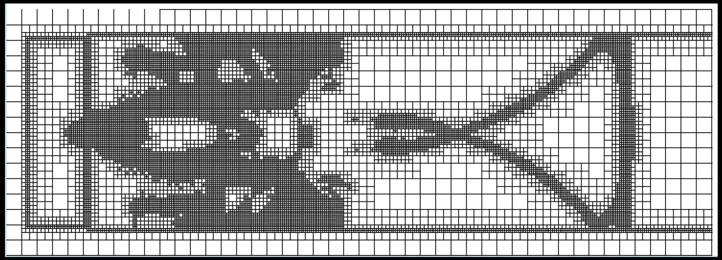
Coastal Flood Inundation

Significant advances in flood inundation modelling …

efficient, dynamically adaptive grid-based models

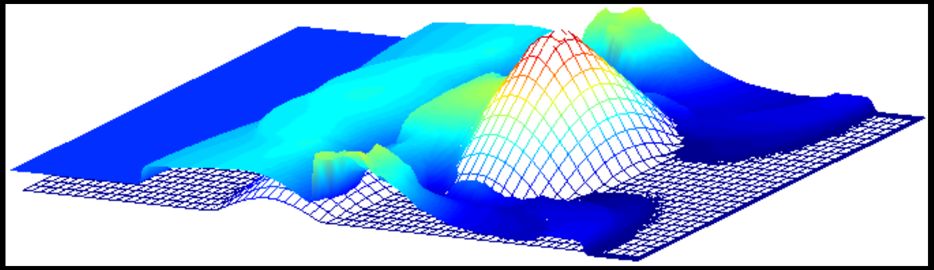
Simulation of dyke break

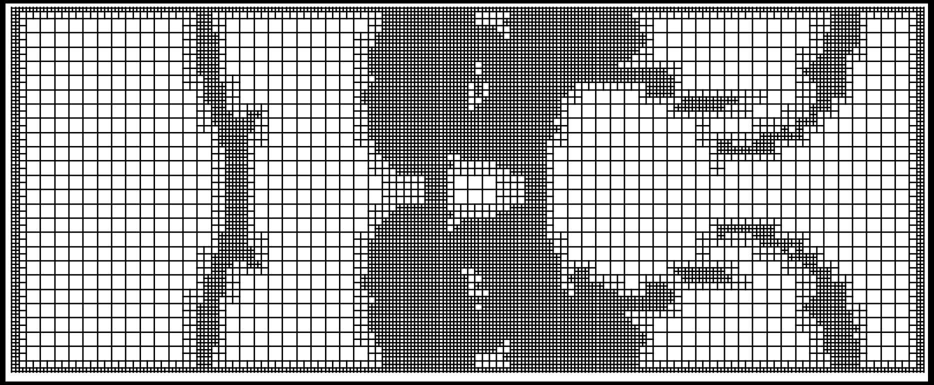




Liang, Borthwick & Stelling 2004

Dam-break wave interaction with three humps

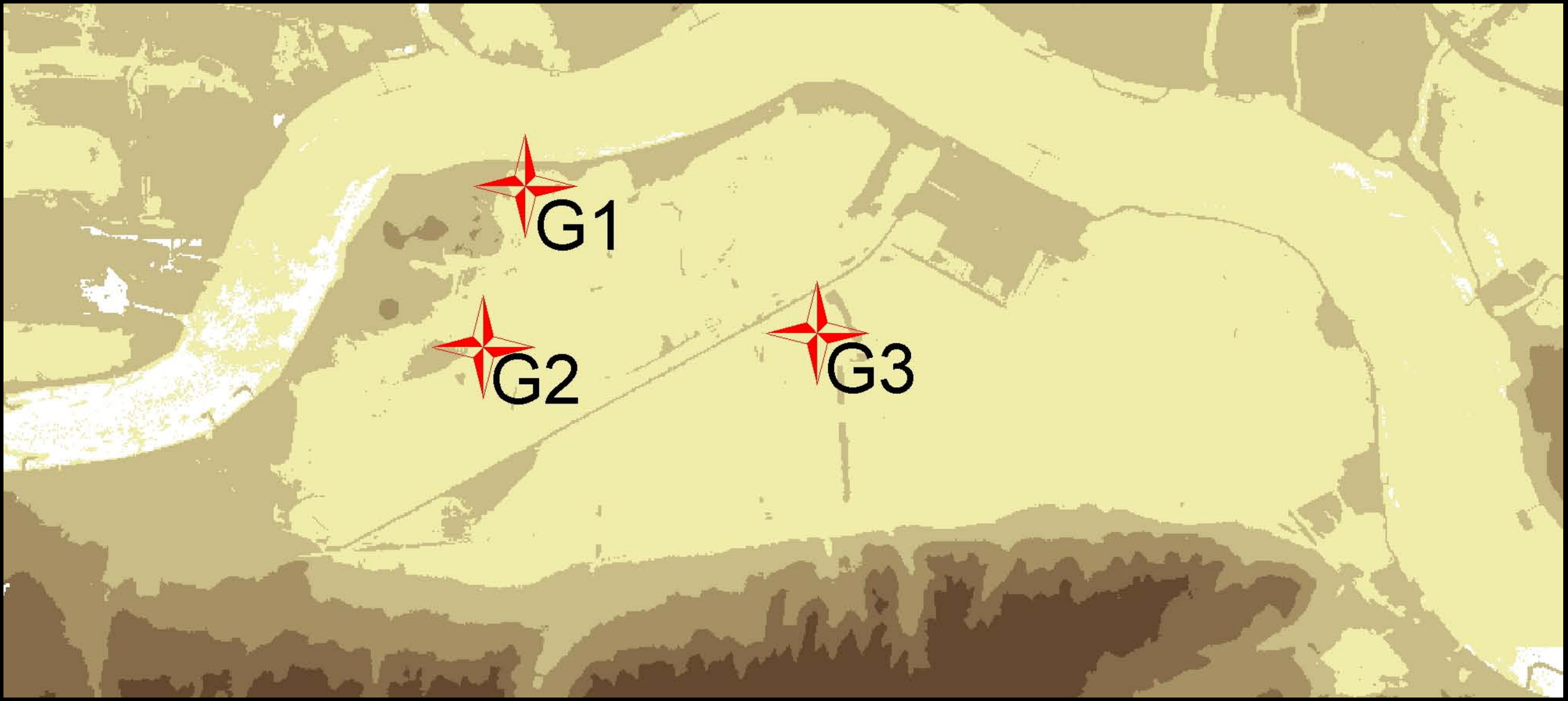




Liang & Borthwick 2009

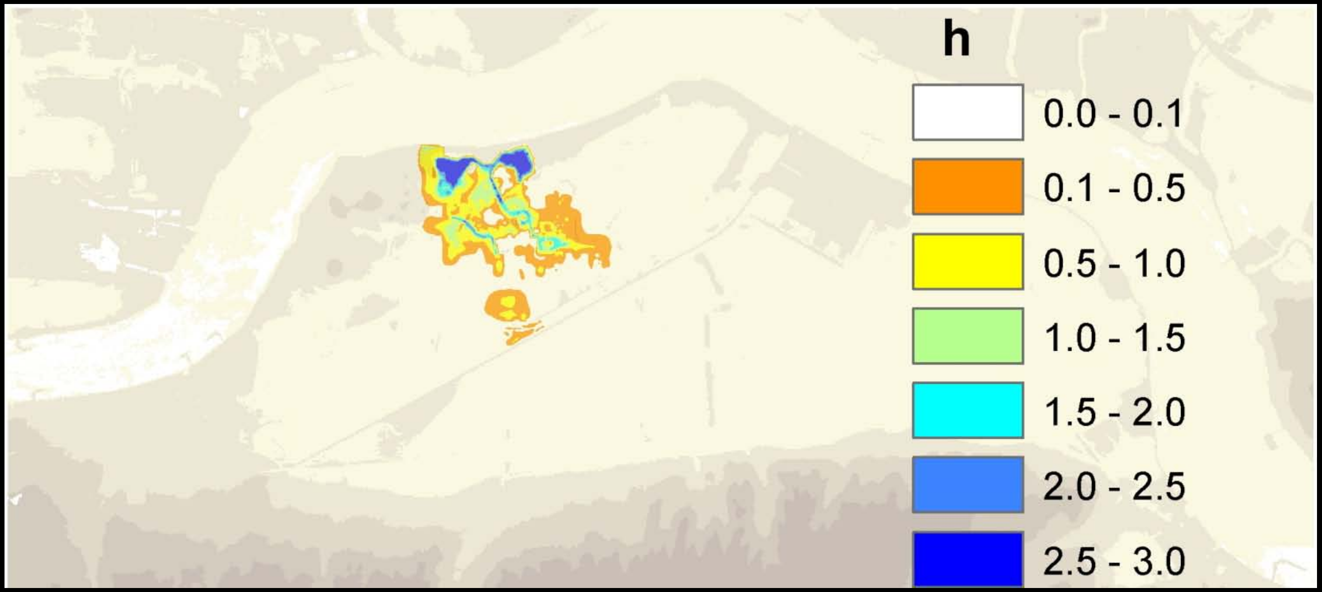
Flood Risk

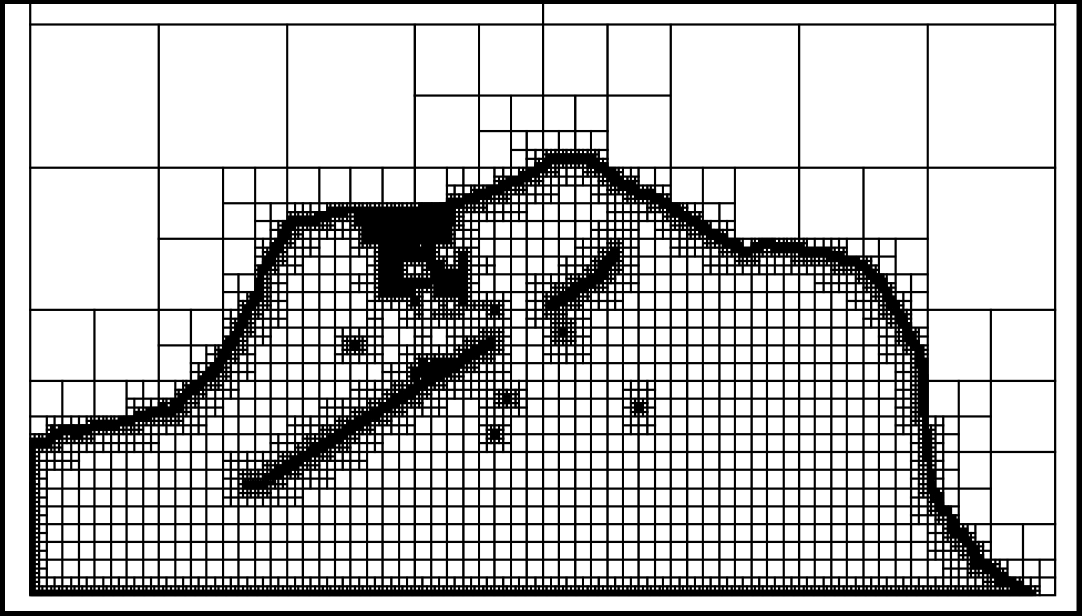
Urban flooding – Thamesmead



Liang, Hall & Borthwick 2008

Flood Risk: Urban flooding – Thamesmead

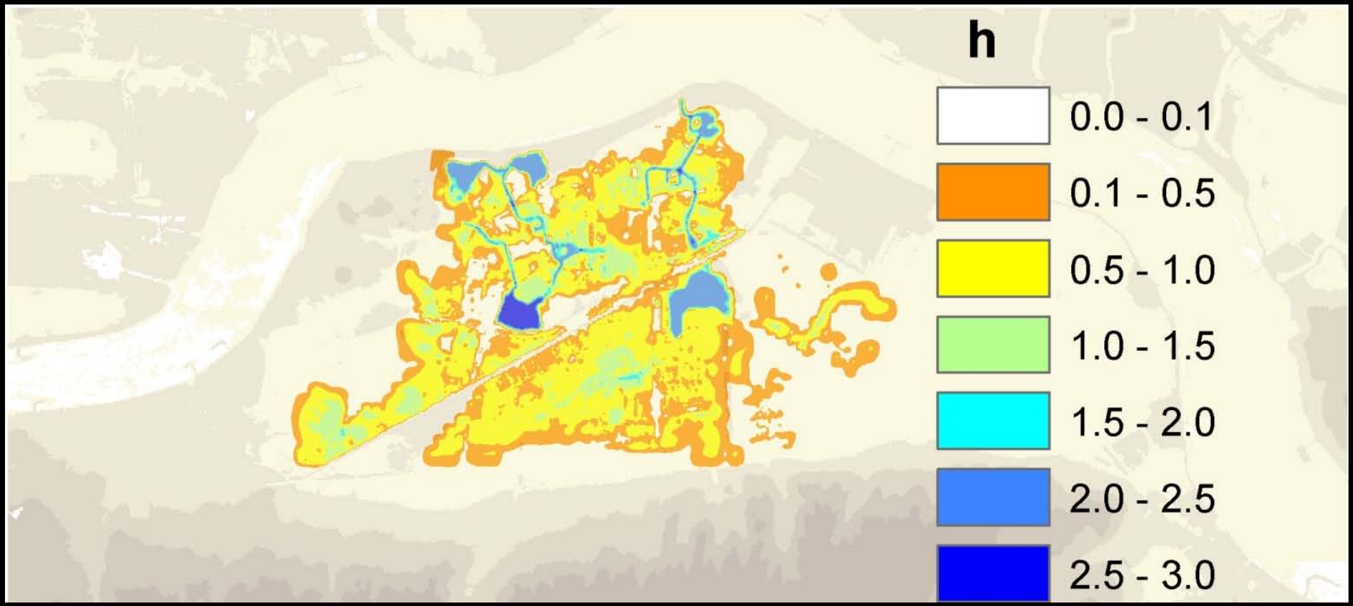




t = 1 hour 40 mins

Liang, Hall & Borthwick 2008

Flood Risk: Urban flooding – Thamesmead



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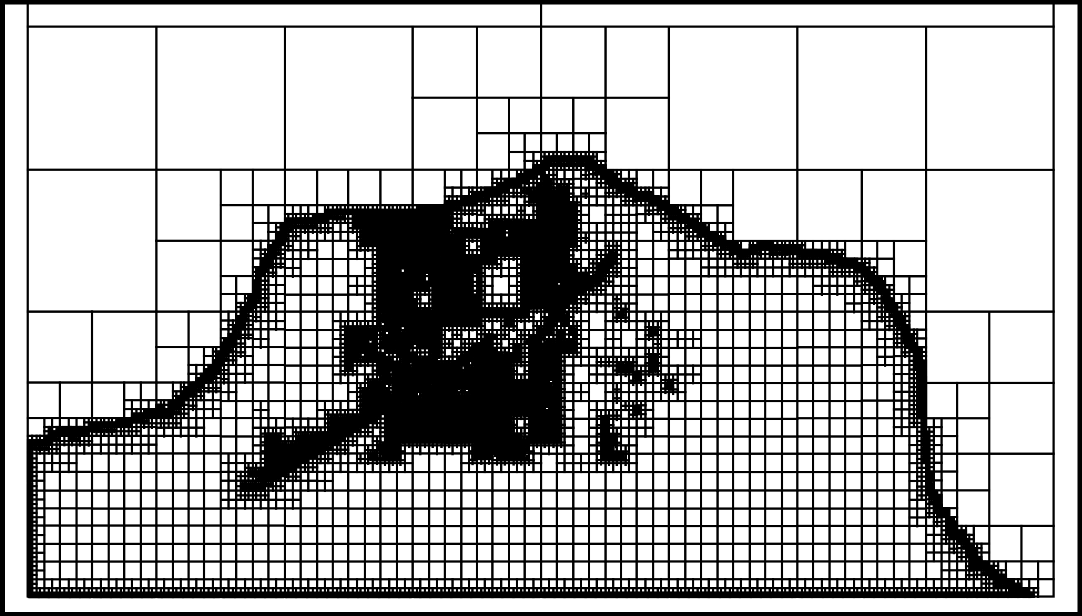


Liang, Hall & Borthwick 2008

Coastal Risk: Advance or Retreat

- Introduction
- Sea level
- Tsunami
- Extreme storm-induced waves
- Breaching
- Coastal flood inundation
- Coastal Erosion

Coastal Erosion

Probabilistic assessment of coastal erosion …

qualitative – ranked order of erosion hazard

quantitative – e.g. stochastic models of shoreline response

Ruins of All Saints Church
Dunwich, England

For sandy beaches, maximum tidal shoreline recession may be determined using separate long-shore and cross-shore beach response models (Dong & Chen, 2001)

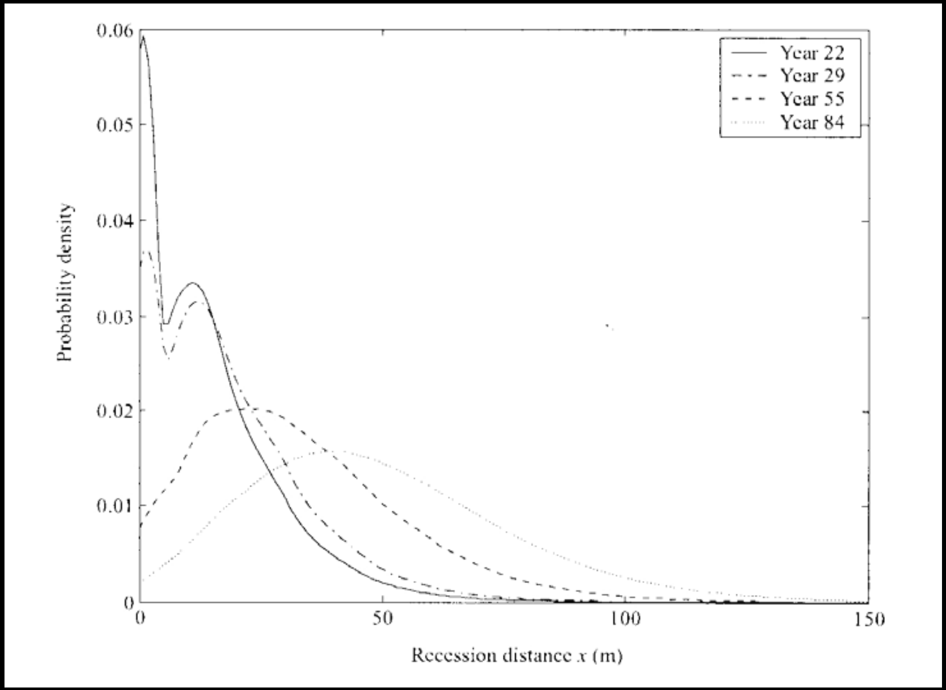
Coastal Erosion

For soft cliffs, retreat events may be modelled as a gamma distributed series of durations between erosion events and a log-normal distributed series of size of landslide

Receding Naze Cliffs, Essex, England

Bristol University

Bayesian prediction of cliff recession



Hall, Meadowcroft & van Gelder 2002

Joint probability distributions provide more accurate estimates of long-term coastal erosion (Callaghan, Ranasinghe & Short 2009)

Sandy cliff erosion

www.panoramio.com/photo/8413174

Holderness, England

www.hull.ac.uk/erosion/processes.htm

Conclusions I

Sea level rise has a very large effect on design levels – exacerbated by climate variability

Effective early warning systems are vitally important

Numerical modelling of solitary waves → insight into tsunami inundation

Empirical methods used for estimating storm-induced run-up and overtopping

Alternative deterministic approach could be to use focused wave groups for storm-induced run-up and overtopping

Conclusions II

Breaching and inundation can be modelled using NSWEs in conjunction with local breach model

Advances are occurring in use of probabilistic techniques for estimating extreme sea levels and coastal erosion, especially the application of joint probability distributions

Many simulations → hazard map (e.g. of inundation levels)

Flood risk = prob. of inundation x vulnerability x asset value

King Cnut the Great (from Charlotte M. Yonge, Young Folks’ History of England, D. Lothrop & Co, Boston, 1879)   Clipart courtesy FCIT

Acknowledgements

Paul Taylor, Rodney Eatock Taylor and Richard Soulsby

Ben Weston, Yao Yao, Kuo Yan, Jana Orszaghova, Ilektra-Georgia Apostolidou, Wei Koon Lee, Scott Draper, Myron van Damme, Mohd Ridza Mohd Haniffah and Mike Ford (Oxford)

Peter Stansby, Ben Rogers and Tong Feng (Manchester)

Alison Hunt-Raby (Plymouth), Qiuhua Liang (Newcastle)

Mark Morris (HRW) and Jinren Ni (PKU)

EPSRC Flood Risk Management Research Consortium

HR Wallingford

Thank you

Environment Agency, 2010