MODELLING TSUNAMIS WITH A NON-HYDROSTATIC VERSION OF THE MOHID MODEL

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Summary

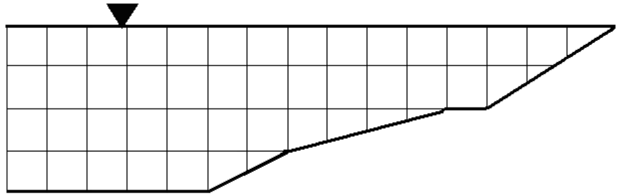
- Motivation
- Model characteristics
- Model benchmarking results and conclusions
- Some examples of the high resolution flood maps for the Portuguese mainland *(if there is still time…)*

Motivation

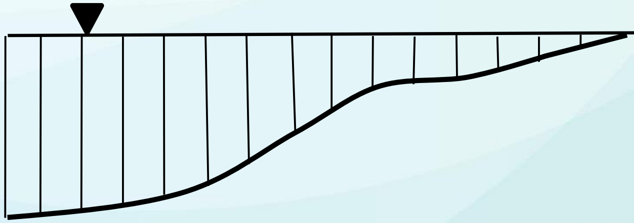
- Hidromod was contracted by the Portuguese Civil Protection Agency (ANPC) to delimit inundation areas of several regions of the Portuguese coast in case of a tsunami event.
- Traditionally this kind of studies have been mainly developed with the aid of hydrostatic models such as COMCOT, MOHID, TUNAMI-N2, COMMIT/MOST, etc.
- Studies following the Boxing Day tsunami suggest the evolution and run-up of tsunamis can be strongly influenced by dispersion due to non-hydrostatic effects. According these studies this can result in **up to 60% higher values** of coastal run-up than the ones calculated by the above referred models.
- For the aforementioned reasons it was decided to take this opportunity to evaluate the added value of introducing non-hydrostatic capabilities in the MOHID modelling system.
- In this presentation there will be described the results of a benchmarking battery tests that were used to assess the reliability of these new capabilities

Innovation

- **Starting point**: MOHID non-hydrostatic version Theias (2005) based in by Casulli & Zanolli (2002)
  - iterative solver
  - valid only to Cartesian grids
  - hydrostatic approximation is assumed in the surface layer as a boundary condition – bad results for wind waves

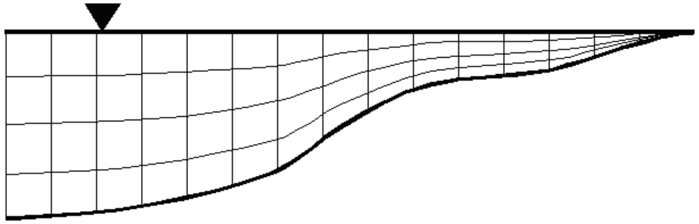


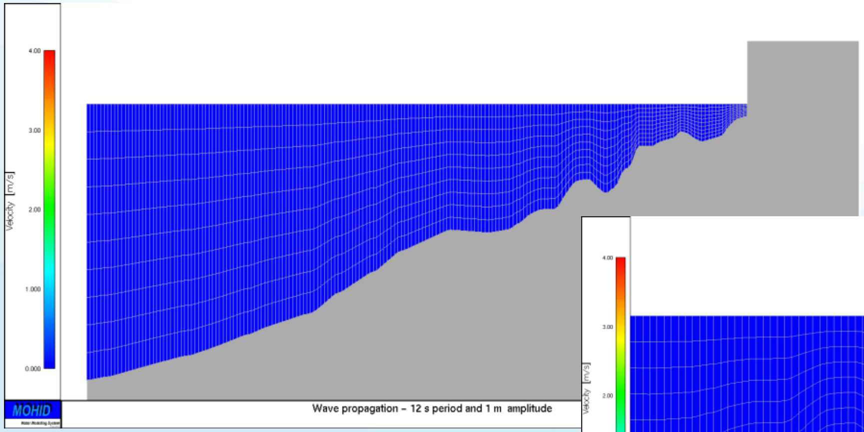
- **This work:** MOHID non-hydrostatic version Silva (2016) based in Cui, H., Pietrzak, J. D., & Stelling, G. S. (2012):
  - Focus in tsunamis
  - ADI => Thomas algorithm (simple solver)
  - One layer with terms that take in consideration the surface and bottom gradients;
  - Equivalent to SWASH with one layer

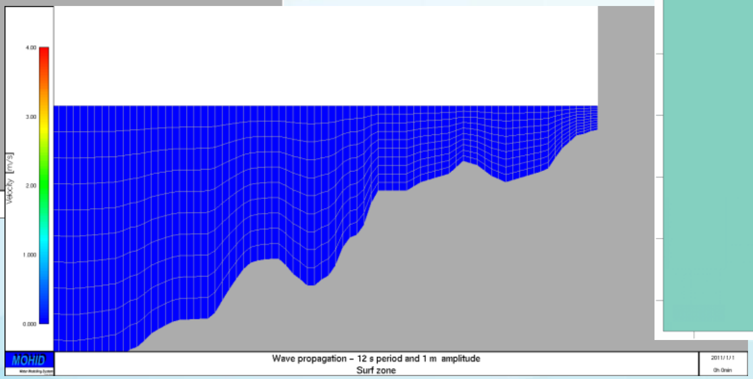


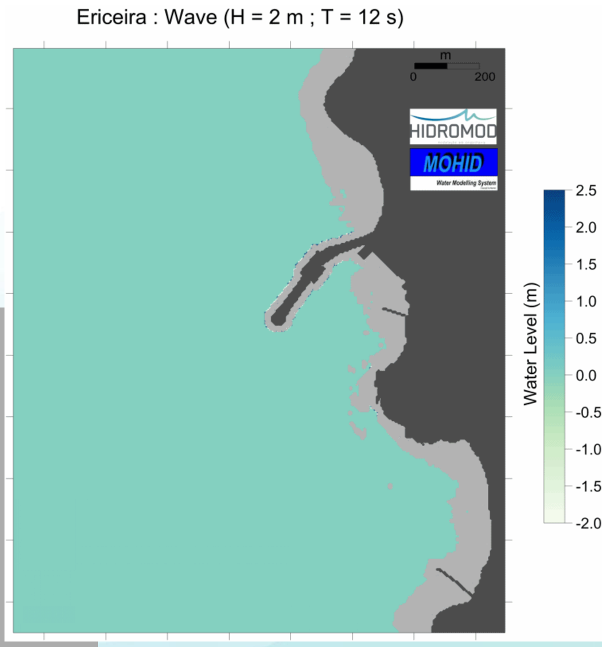
Perspectives for development

- MOHID non-hydrostatic based in Stelling, G., & Zijlema, M. (2003).
  - Focus in wind waves. SWASH type model;
  - 3D – generic coordinate (e.g. Sigma, ...)
  - Extra pressure correction terms associated with layer thickness gradients;









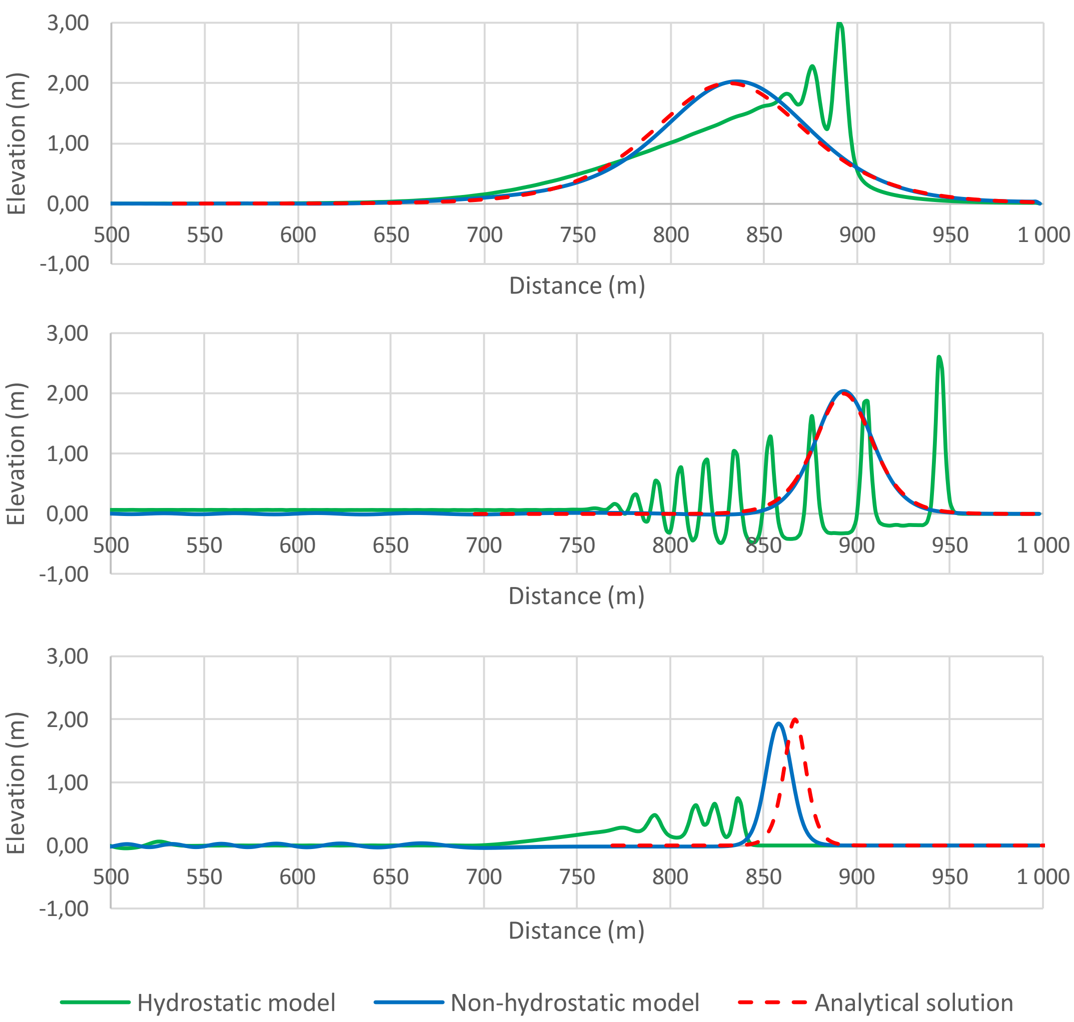
Benchmarking

Benchmarking Steps:

(Based on the benchmarking methodology proposed by NOAA. More information at http://nctr.pmel.noaa.gov/benchmark/)

Analytical Benchmarking	• Propagation of a solitary wave on a flat bottom channel.
Laboratory Benchmarking	• Solitary wave on a simple beach. • Solitary wave on a composite beach. • Solitary wave on a conical island. • Monai Valley wave tank.
Field Benchmarking	• Tohoku tsunami.

Analytical benchmarking: Solitary wave on a channel



Model conditions

- Relative wave amplitude **(A/h) = 0.125**
- Spatial step = 2 m
- Time step = 0.05s

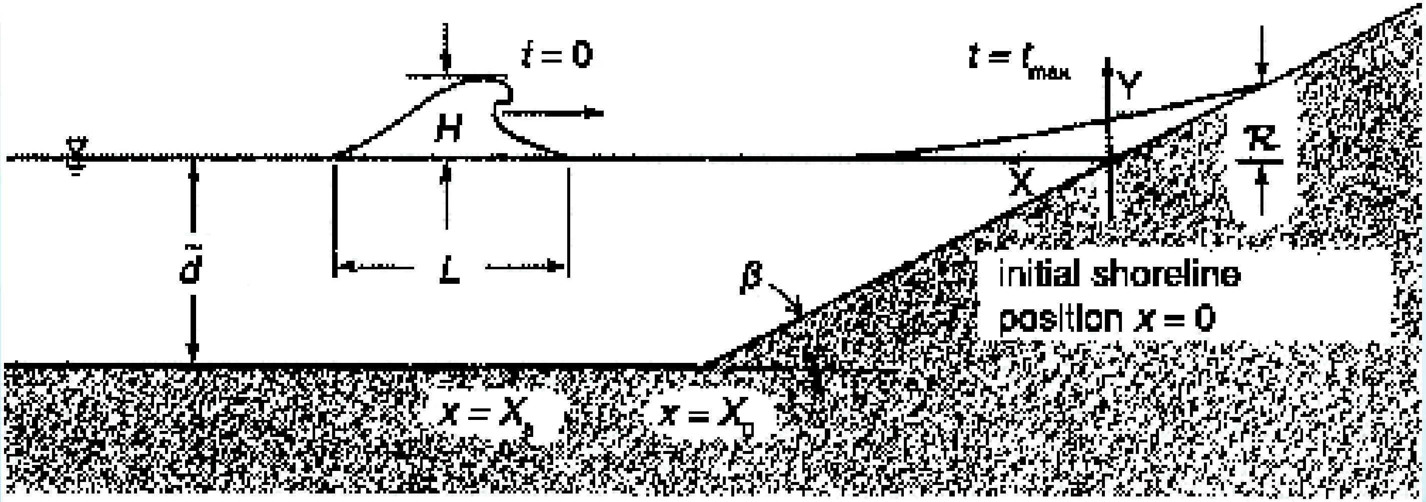
- Relative wave amplitude **(A/h) = 0.250 m**
- Spatial step = 2 m
- Time step = 0.05s

- Relative wave amplitude **(A/h) = 0.500 m**
- Spatial step = 2 m
- Time step = 0.01s

Laboratory benchmarking: Solitary wave on a simple beach

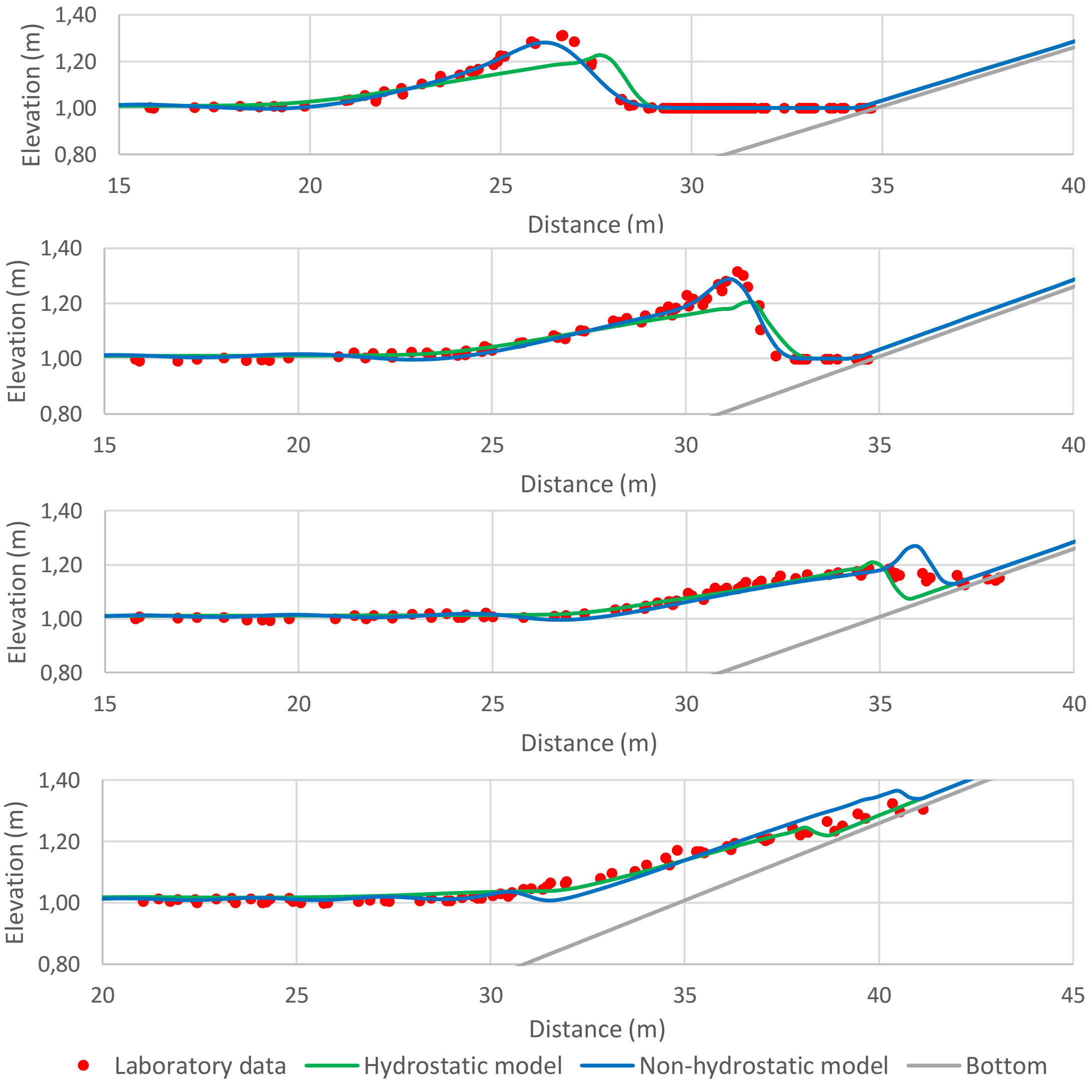
Test description

- Propagation of 2 solitary waves with relative amplitudes of 0.0185 and 0.3 on a channel.
- The channel ends in a ramp with a slope of 1:19.85.
- The objective of the test is to model the canonical problem of a constant-depth region adjoining a sloping beach.



Definition sketch for the canonical problem of a constant-depth region adjoining a sloping beach. Taken from Synolakis *et al.* (2007)

Laboratory benchmarking: Solitary wave on a simple beach



Model conditions

- Relative amplitude (A/h) = 0.3
- Spatial step = 3 m
- Time step = 0.01 s
- T = 15

- T = 20

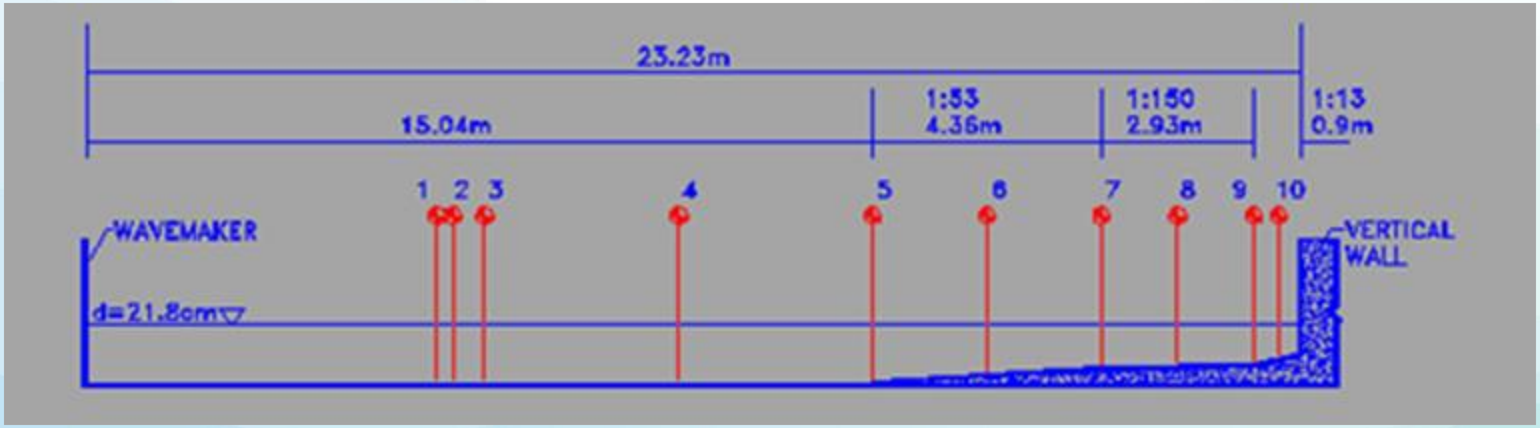
- T = 25

- T = 30

Laboratory benchmarking: Sol. wave on a composite beach

Test description

- Propagation of 3 solitary waves with relative amplitudes of 0.039, 0.264 and 0.696 on a physical model representing Revere Beach (Massachusetts, USA) composite beach geometry.
- The model consists of three linear slopes of 1:53, 1:150 and 1:13 from seaward to shoreward with a vertical wall at the shoreline.
- Wave gages placed along the physical model measured surface wave elevations for each test and the gathered data was compared to the results produced by MOHID.

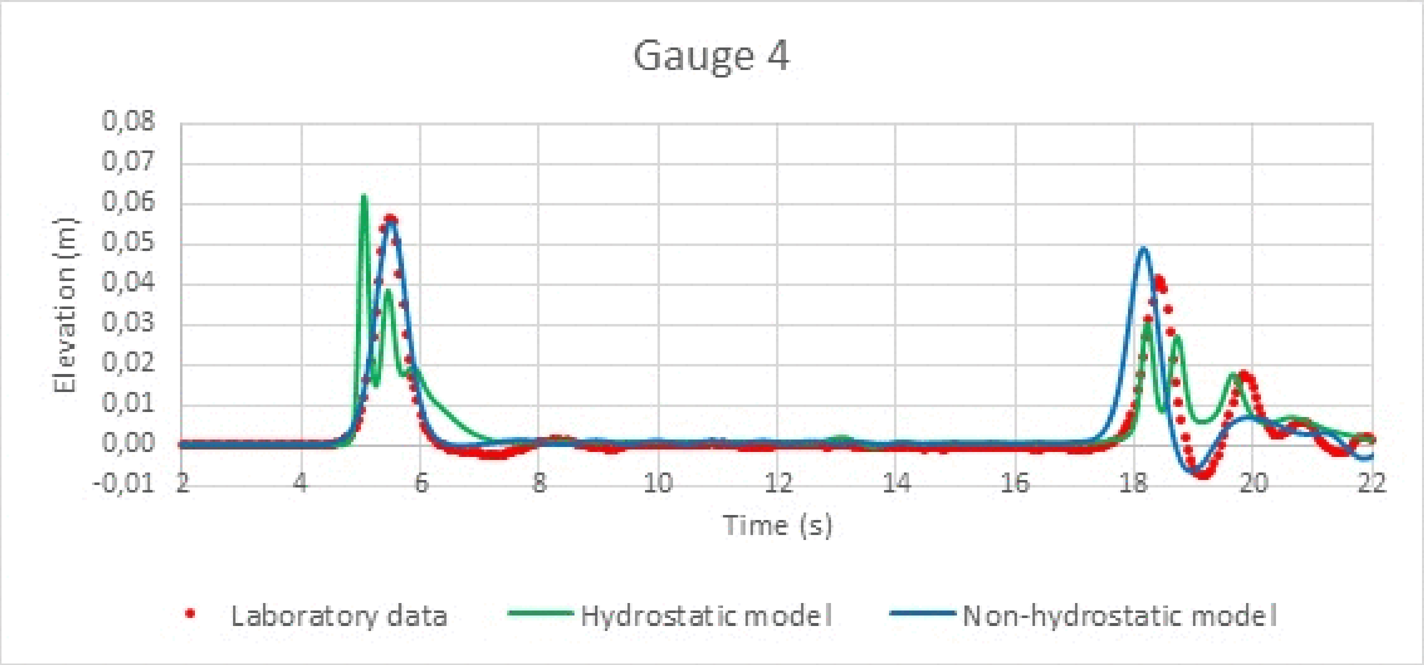


Schematic of flume and gauge layout for the physical model of Revere Beach. Taken from US Army Corps of Engineers (2016).

Laboratory benchmarking: Sol. wave on a composite beach

Model conditions

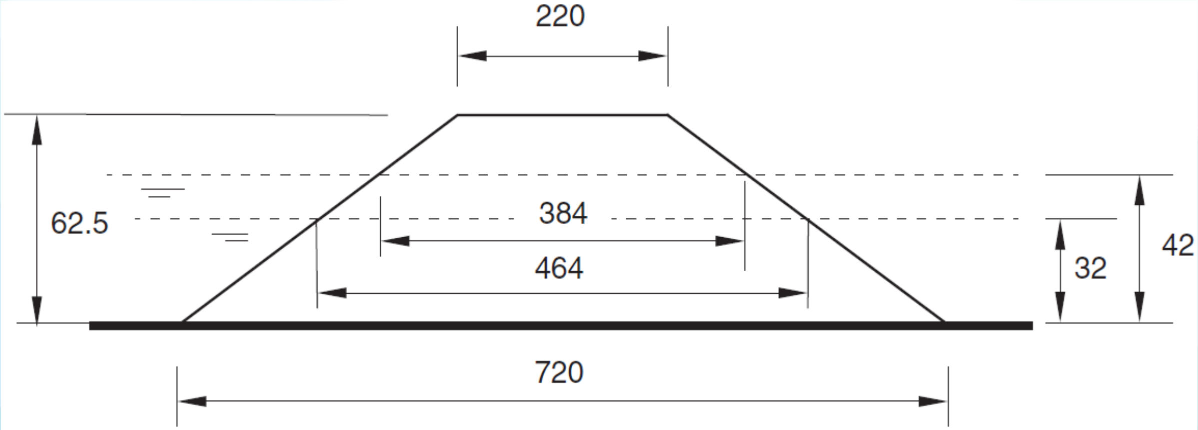
- Relative amplitude (A/h) = 0.264
- Spatial step = 1.2 m
- Time step = 0.02 s



Laboratory benchmarking: Sol. wave on a conical island

Test description

- Propagation of 3 solitary waves with relative amplitudes of 0.045, 0.096 and 0.181 on a flat bottom, 30-m-wide by 25-m-long, tank with the physical model of a conical Island at it's center.
- The island had the shape of a truncated, right circular cone with diameters of 7.2 m at the toe and 2.2 m at the crest.
- The vertical height of the island was approximately 62.5 cm with a slope of 1:4 on it's beach face

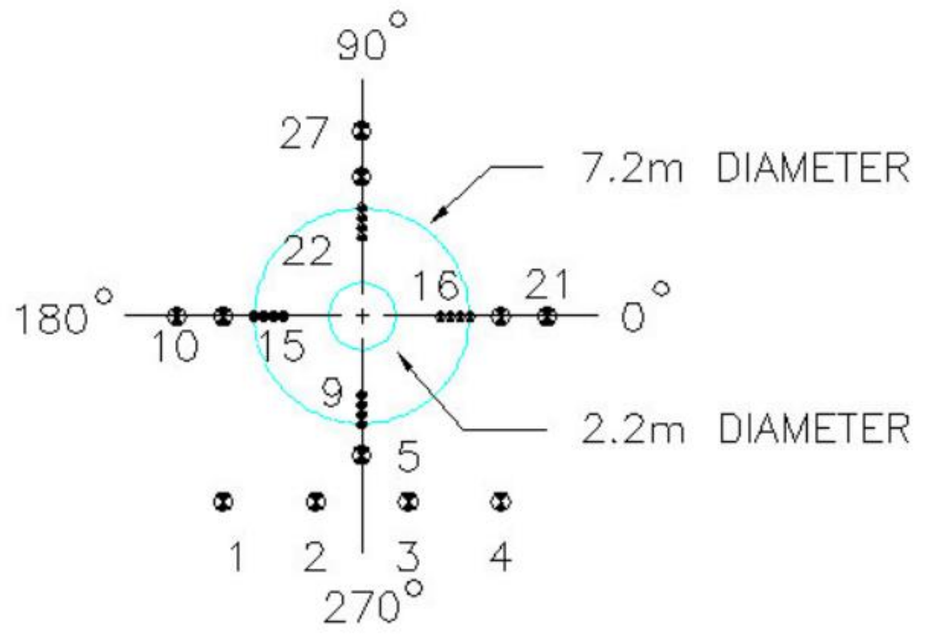


Definition sketch of the conical island. Dimensions in centimetres. Not to scale. Taken from Synolakis et al. (2007)

Laboratory benchmarking: Sol. wave on a conical island

Test description

- Several wave gauges were placed around the beach face of the conical island and the time series recorded by gauges 6, 9, 16 and 22 were compared to the results produced by MOHID.

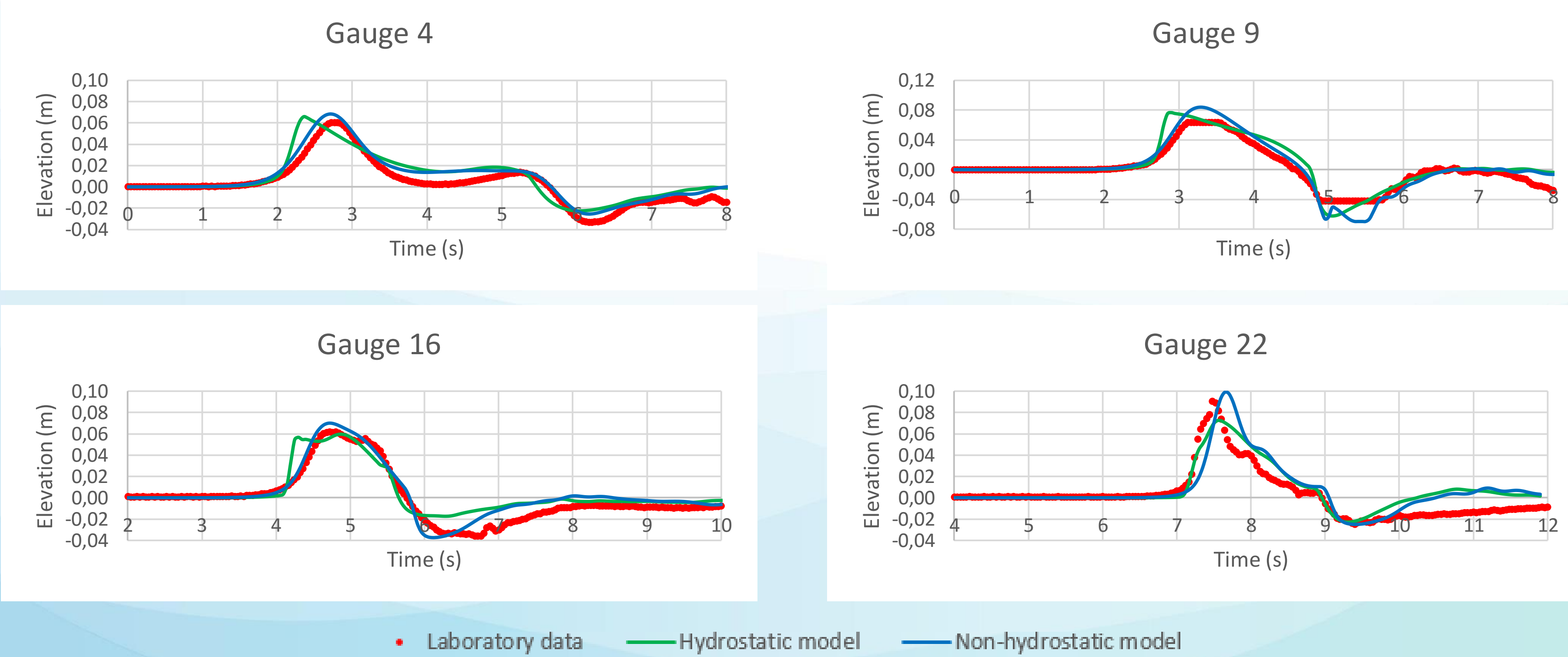


Definition sketch of the conical island. Dimensions in centimetres.
Not to scale. Taken from Synolakis et al. (2007)

Laboratory benchmarking: Sol. wave on a conical island

Model conditions

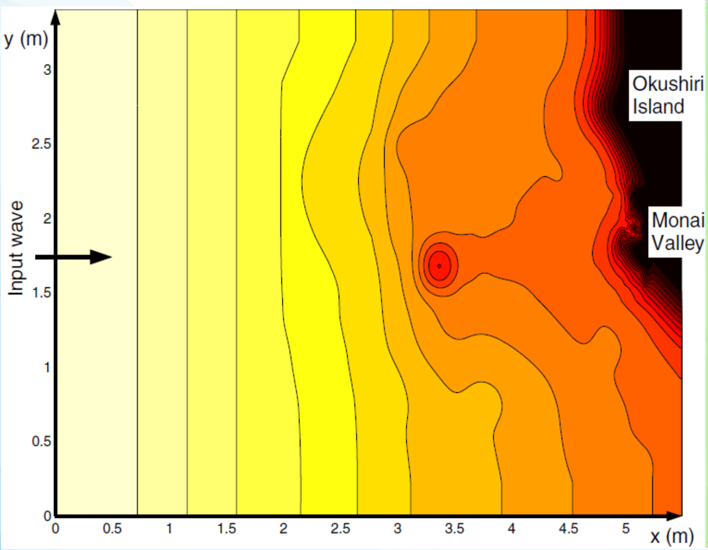
- Relative amplitude (A/h) = 0.181
- Spatial step = 5 m
- Time step = 0.01 s

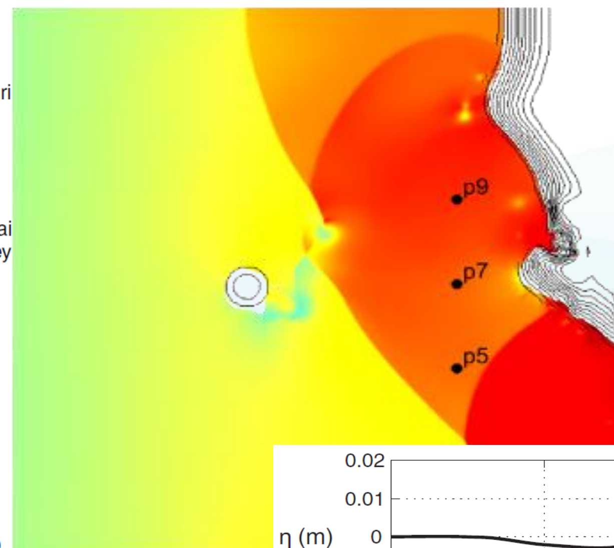


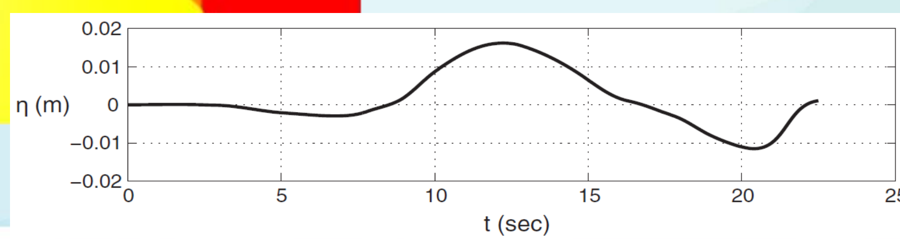
Laboratory benchmarking: Monai Valley wave tank

Test description

- This test is based on experimental data obtained in a wave tank in order to understand the extreme runups observed near the village of Monai during the 1993 Okushiri tsunami.
- The bathymetry and initial wave profile used for the simulation in the numerical models are presented below.



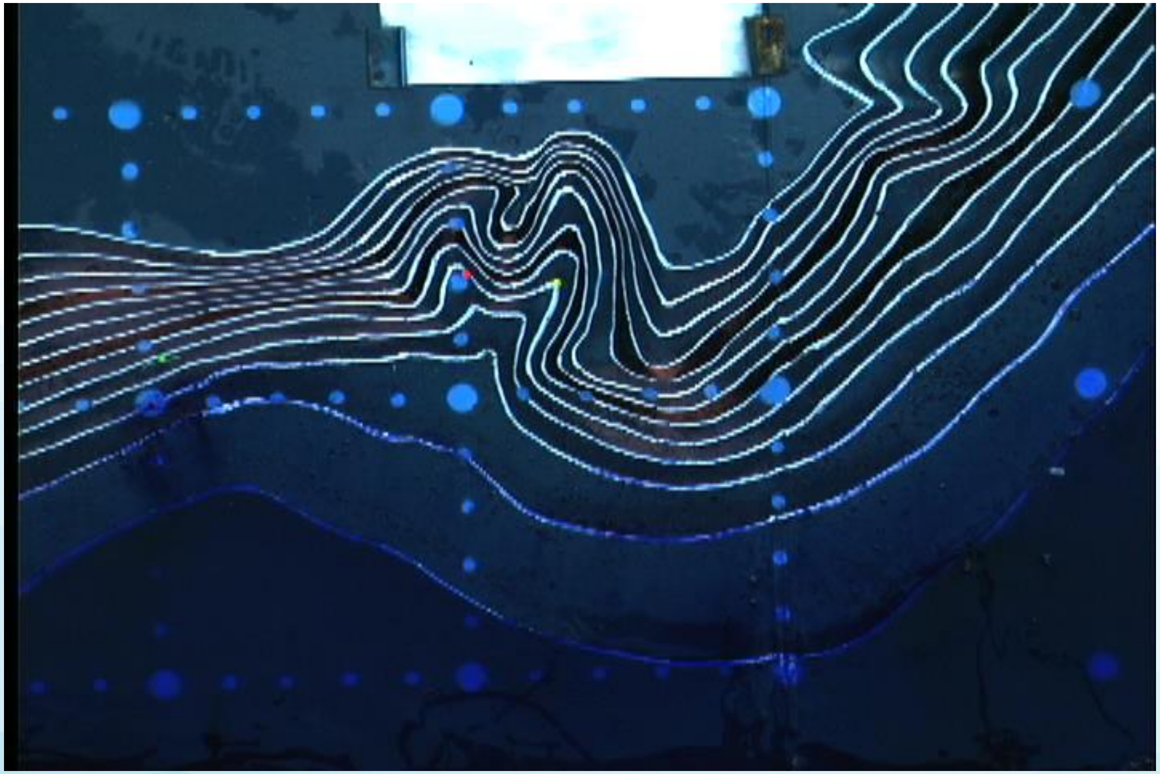




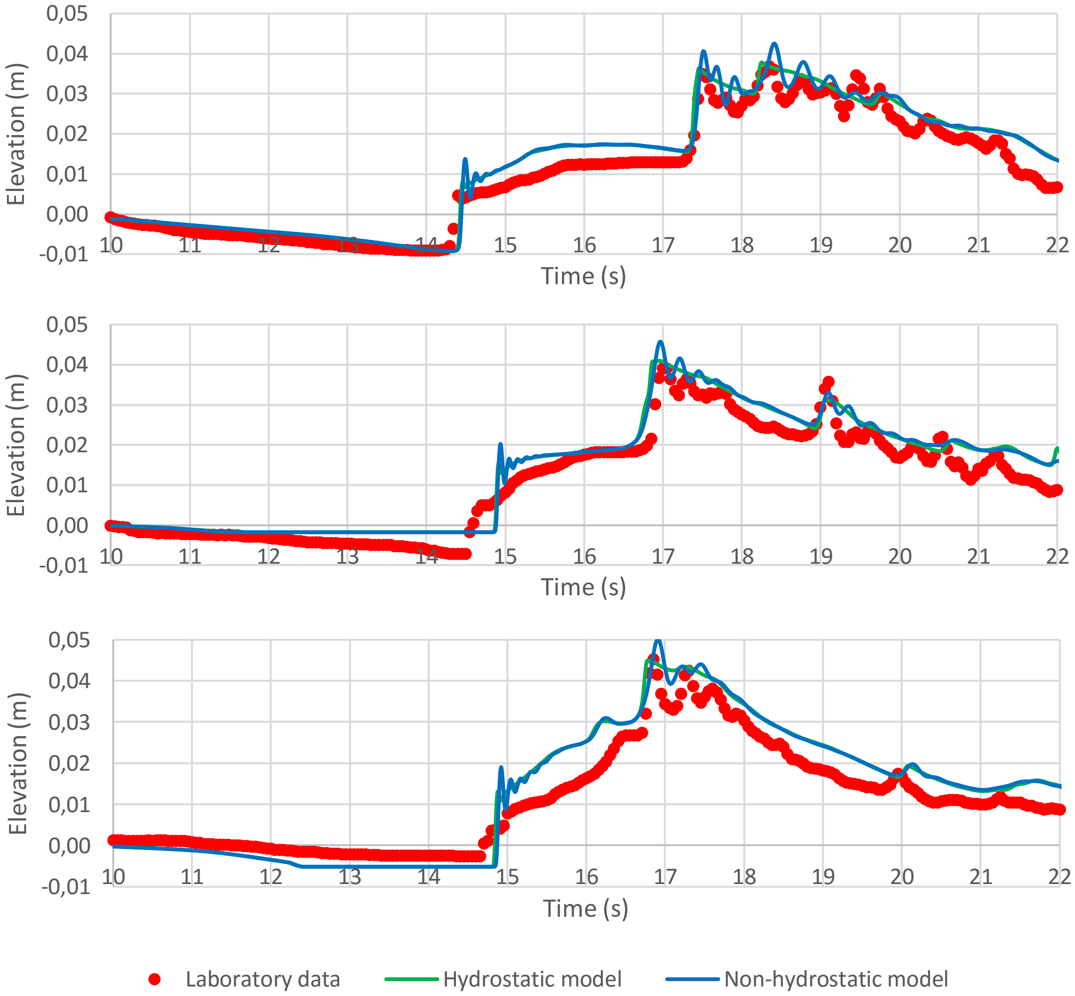
Images taken from (Synolakis *et al.* 2007)

Laboratory benchmarking: Monai Valley wave tank

Video of the experiment
(Downloadable at http://nctr.pmel.noaa.gov/benchmark/Laboratory/Laboratory_MonaiValley/index.html)



Laboratory benchmarking: Monai Valley wave tank



Model conditions

- Spatial step = 1.4 m
- Time step = 0.01s
- Gauge P9

- Gauge P7

- Gauge P5

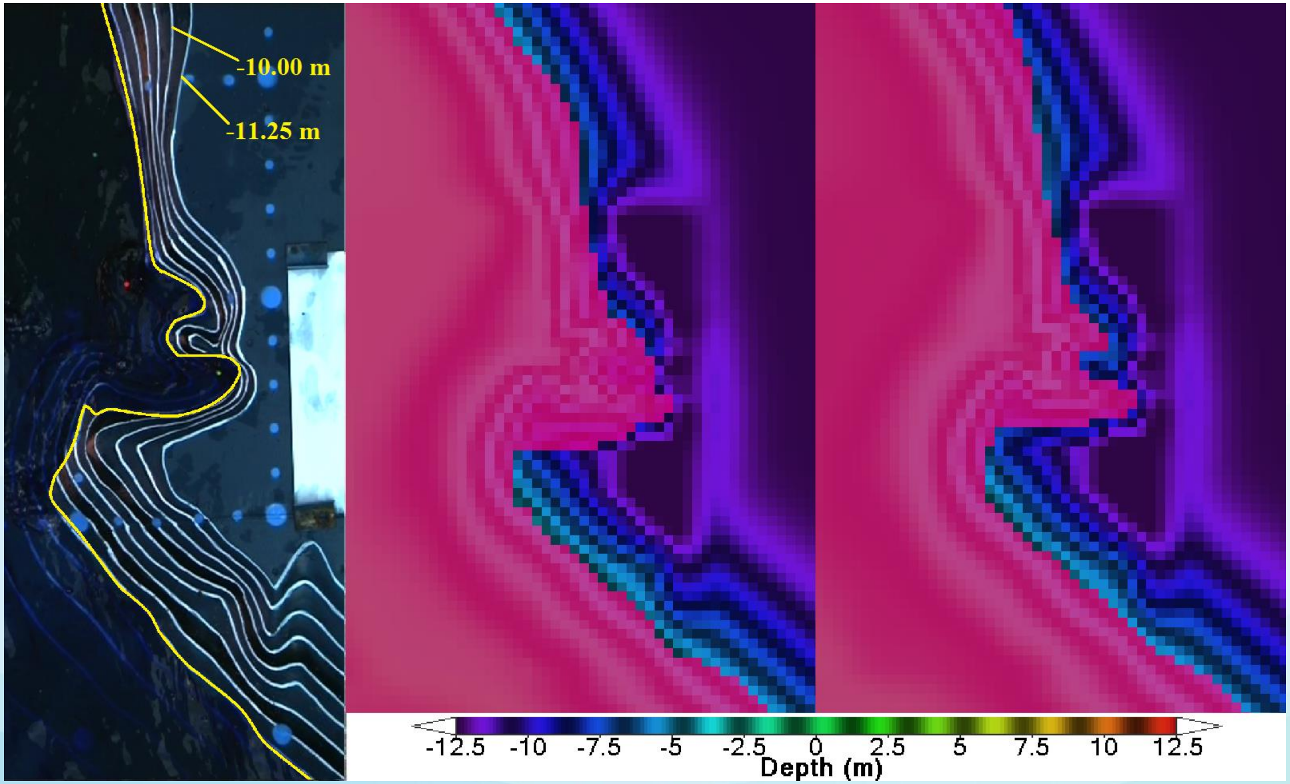
Laboratory benchmarking: Monai Valley wave tank

Maximum run-up values

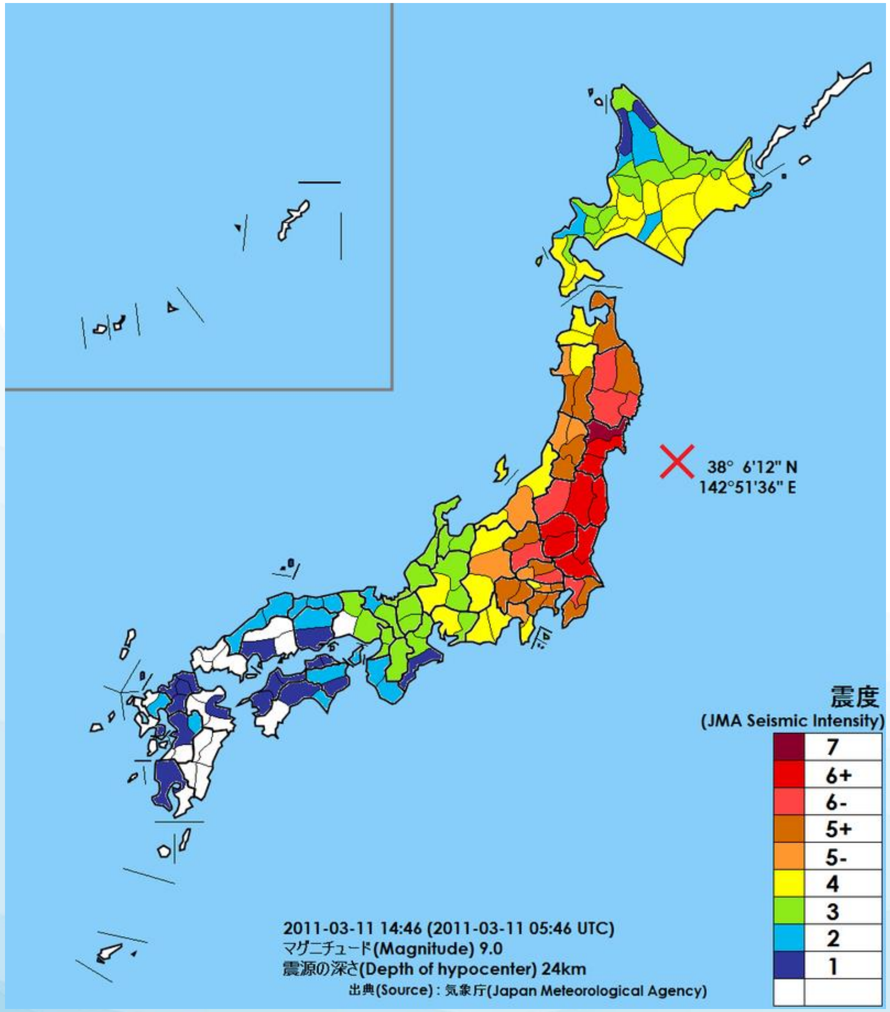
Experiment's screenshot
Max ≈ 10 m

Non-hydrostatic model
Max = 10.15 m

Hydrostatic model
Max = 8.17 m



Field benchmarking: Tohoku earthquake and tsunami



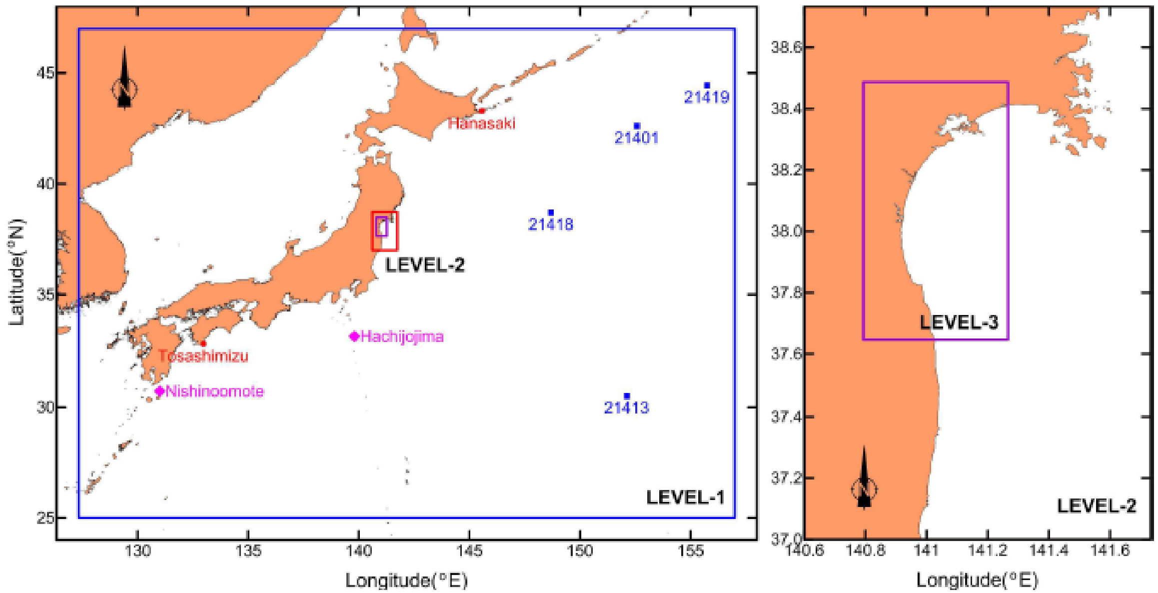
Event description

(Wikipedia, 2016)

- The Tohoku earthquake was a magnitude 9.0 megathrust earthquake off the coast of Tohoku, Japan that occurred on 11 March 2011.
- The epicentre was located 70 km east of the Oshika Peninsula of Tohoku with a hypocentre at an underwater depth of approximately 30 km.
- This earthquake was the largest ever recorded in Japan and the fourth worldwide.
- This event triggered a tsunami which propagated more than 5 km inland on the Sendai Plain, with waves reaching heights of up to 39.7 m
- This tsunami left a terrible aftermath of ten thousand casualties and damage costs of 309 billion US Dollars

Field benchmarking: Tohoku earthquake and tsunami

Model	Modeled Area	Resolution	Number of Grid cells		Δt(sec)
			x	y	
Level-1	25.0000~47.0000 °N 127.3333~157.0000 °E	1/30 °	890	660	10
Level-2	37.0~38.7333 °N 140.6000~141.7333 °E	1/150 °	170	260	5
Level-3	37.6467~38.4867 °N 140.7933~141.2666 °E	1/600 °	284	504	5



Characteristics of the simulation domain with a three-level nesting grid system including observation stations: DART buoy (blue squares), IOC (red circles), and JCG (pink diamonds). Taken from Hyun et al. (2013)

Model conditions

- Tidal gauge data, bathymetry and fault parameters for generation of the initial water level conditions were supplied by the Korean Ocean Research and Development Institute (KORDI) and mirrored the ones presented in Hyun *et al.* (2013).
- The simulations were done on a 3 level nesting grid shown on the left.

Field benchmarking: Tohoku earthquake and tsunami

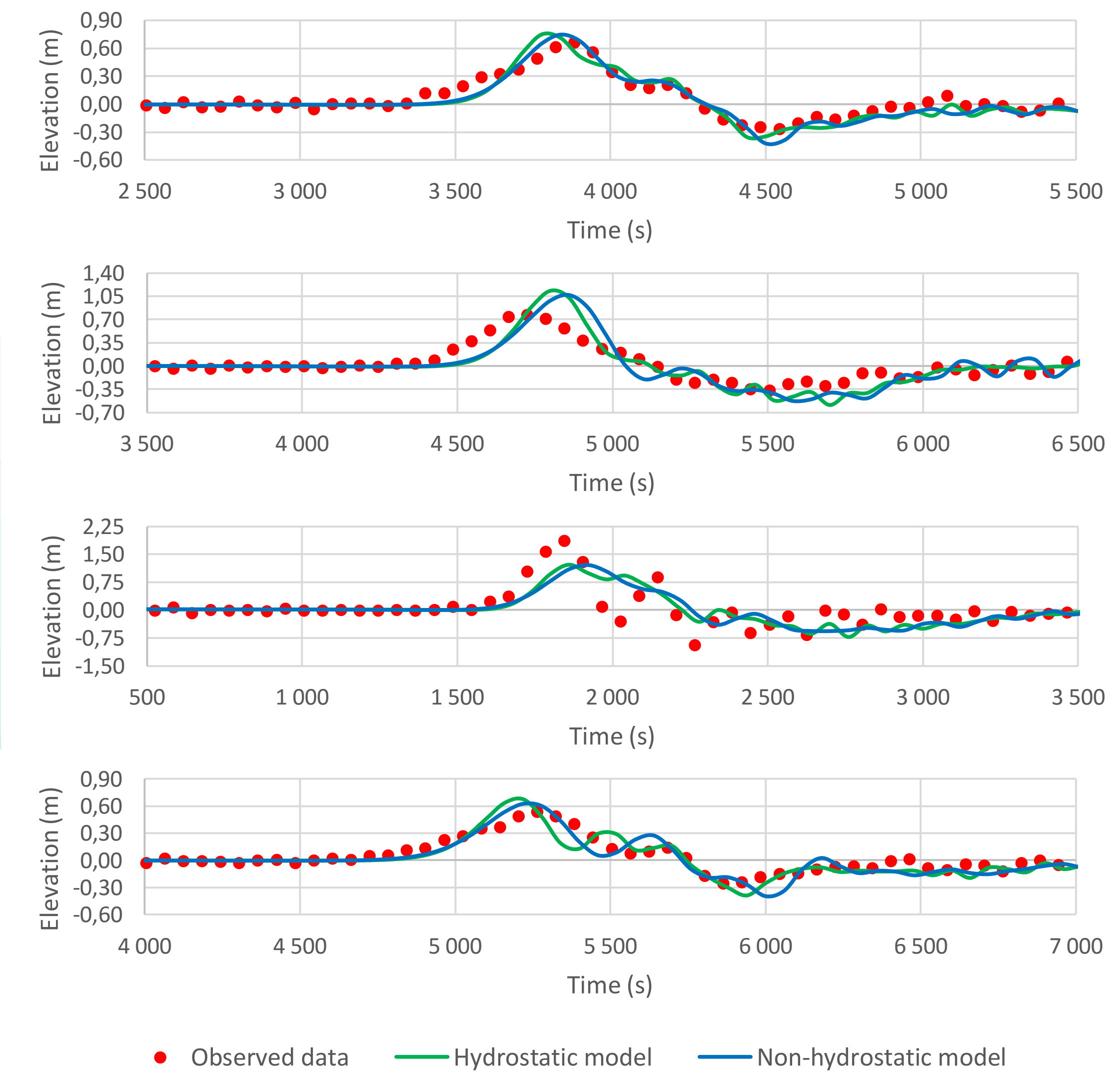
Model conditions

- The initial water displacement caused by the earthquake was calculated using the tsunami modelling package COMCOT (v1.7) which follows the fault plane model proposed by Okada (1985). The fault parameters are presented below.

	Lat. (°)	Lon. (°)	Depth (Fault Top, km)	Length (km)	Width (km)	Strike (°)	Dip (°)	Rake (°)	Slip (m)	M_w
Fault 1	38.80	144.00	5.1	186	129	203	16	101	24.7	8.8
Fault 2	37.33	142.80	17.0	194	88	203	15	83	6.1	8.3

Fault parameters for the 2011 Tohoku earthquake. Taken from (Hyun et al. 2013).

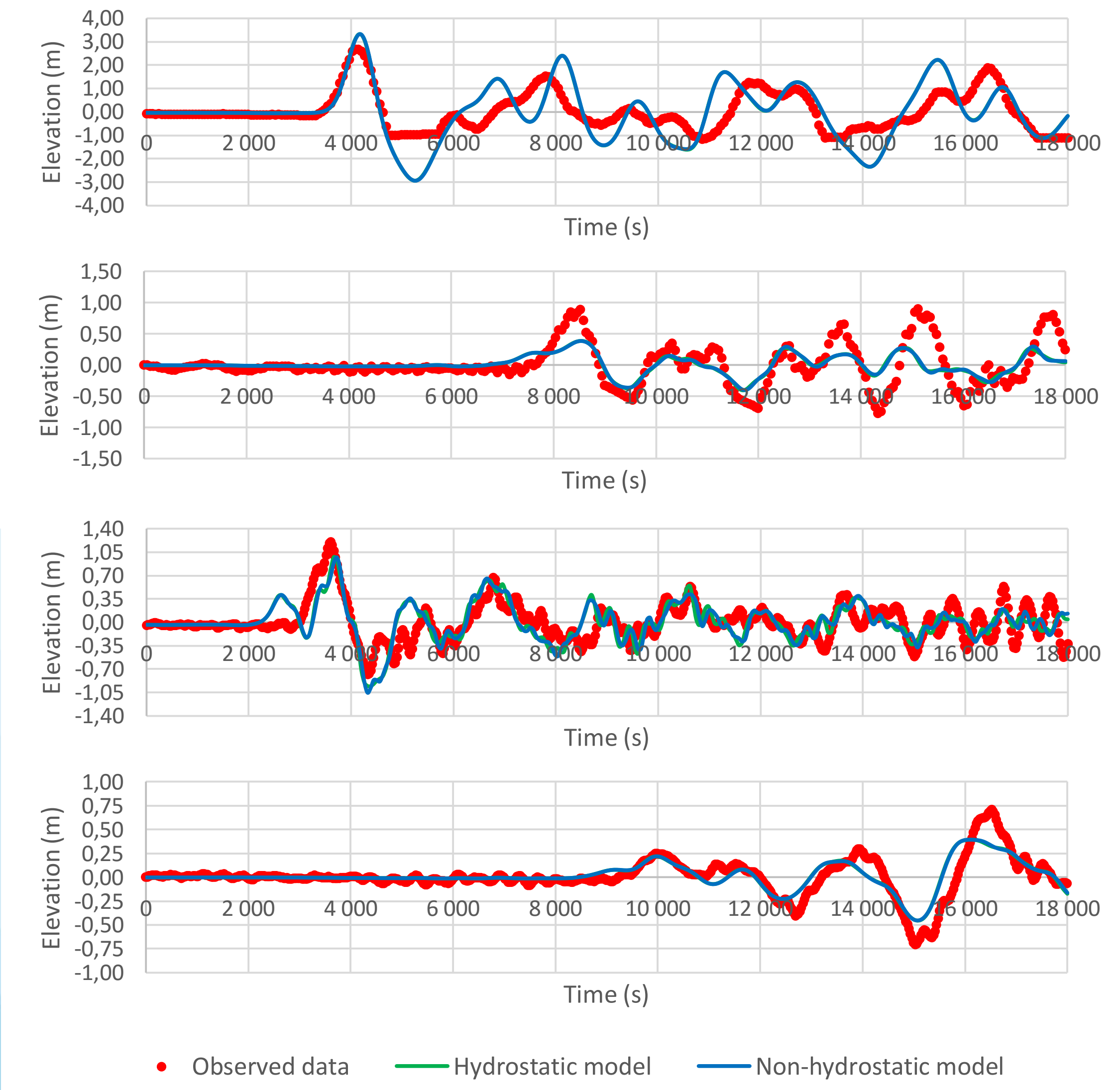
Field benchmarking: Tohoku earthquake and tsunami



Data comparison

- DART buoy 21401
- DART buoy 21413
- DART buoy 21418
- DART buoy 21419

Field benchmarking: Tohoku earthquake and tsunami



Data comparison

- IOC station - Hanasaki
- IOC station - Tosashimizu
- JCG - Hachijojima
- JCG - Nishinoomote

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Conclusions

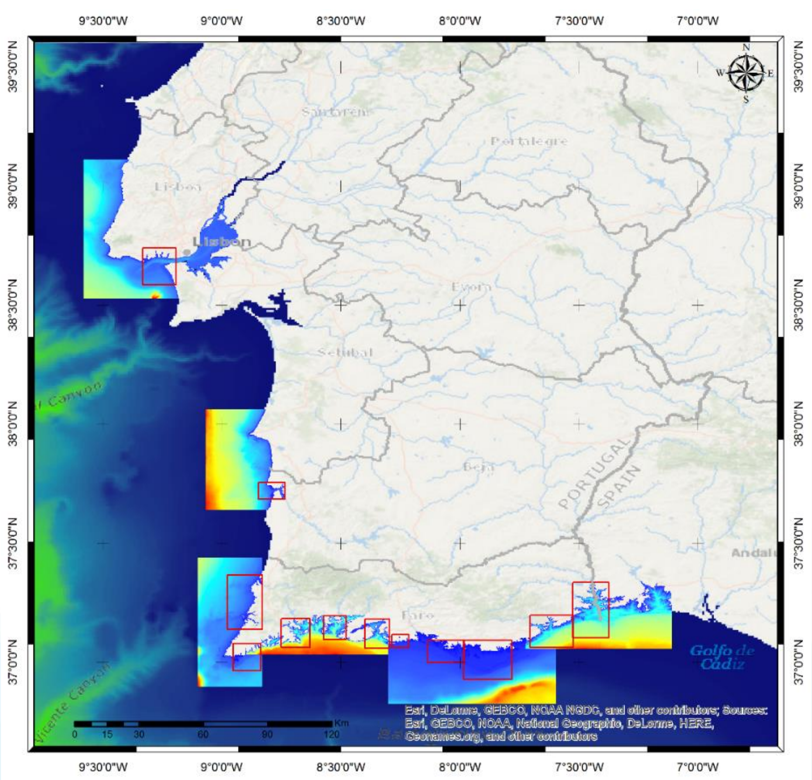
Main takeaways

- From the overall good fitting obtained for all the proposed test cases, the non-hydrostatic model appears to be ready for use in tsunami modelling.
- When compared to the hydrostatic version of MOHID, the non-hydrostatic model displayed much better results in tests where the vertical acceleration component was more relevant.
- In the tests that were more similar to real tsunami events the difference between models was less significant. This can be explained by by the fact that tsunami waves' propagation in the open sea can be approximated by the shallow water equations, which assume a small vertical velocity of the fluid (nearly hydrostatic).
- Non-hydrostatic MOHID was consistently better at estimating maximum run-up values.

High Resolution Flood Maps for the Portuguese Mainland

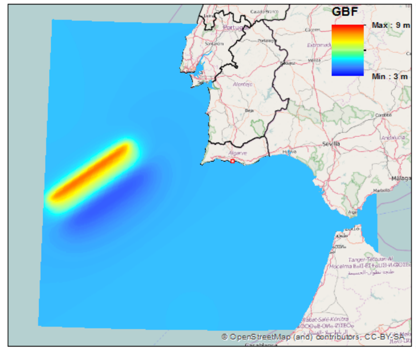
Model Implementation

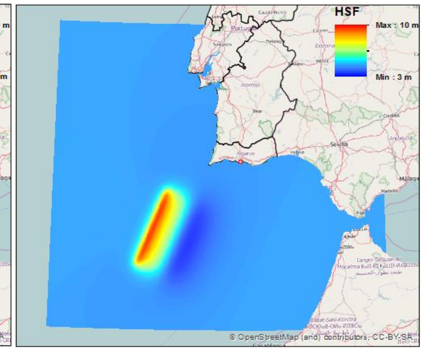
- Three nested grid levels over the Portuguese coast model
  - ✓ *Level 1: 800 m*
  - ✓ *Level 2: 200 m (6 regions)*
  - ✓ *Level 3: 50 m (12 specific sites)*
- Initialization
  - ✓ *Sea level rising (Okada model)*
- Water level
  - ✓ *A water level of 4.50 meters was considered to take in consideration the maximum astronomical tide and maximum storm surge effect*
- Boundary Conditions
  - ✓ *Flather (1976) radiation*
  - ✓ *One way nesting*

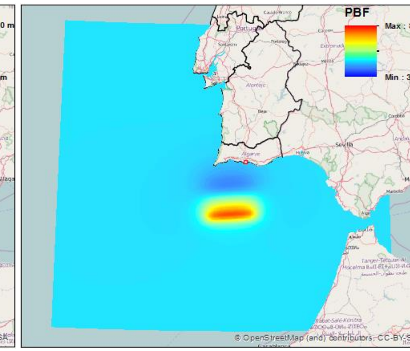


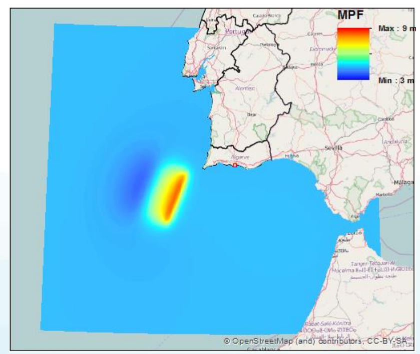
Performed simulations

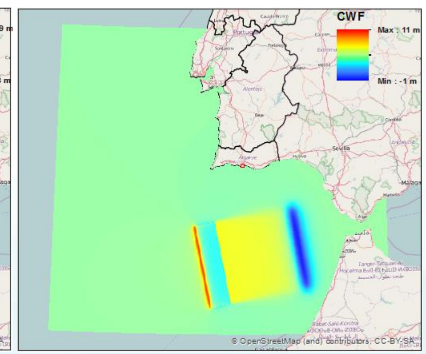
- **Five tsumani sources**
  - ✓ *Gorringe Bank Fault*
  - ✓ *Horse Shoe Fault*
  - ✓ *Marques Pombal Fault*
  - ✓ *Portimão Bank Fault*
  - ✓ *Cadiz Wedge Fault*











- **Results/Products**
  - ✓ *Max inundation maps*
  - ✓ *Max water column maps*
  - ✓ *Max velocity maps*
  - ✓ *Max hazard maps*
  - ✓ *First wave time arrival and wave height for the hole country.*

Cenário	L (km)	W (km)	Epicentro Lon	Epicentro Lat	D (km)	slip (m)	Strike (º)	Dip (º)	Rake (º)	Referência
GBF	200	60	-11.332	36.665	25.0	8.3	53.0	25.0	90.0	Wronna et al, 2015
HSF	165	70	-9.913	35.796	25.0	10.7	22.1	25.0	90.0	Baptista et al, 2008
MPF	110	70	-9.890	36.574	25.0	8.0	20.0	35.0	90.0	Wronna et al, 2015
PBF	100	55	-8.585	36.314	25.0	7.2	266.3	25.0	90.0	Baptista et al, 2008
CWF	170	200	-8.059	35.407	5.0	20.0	349.0	5.0	90.0	Wronna et al, 2015

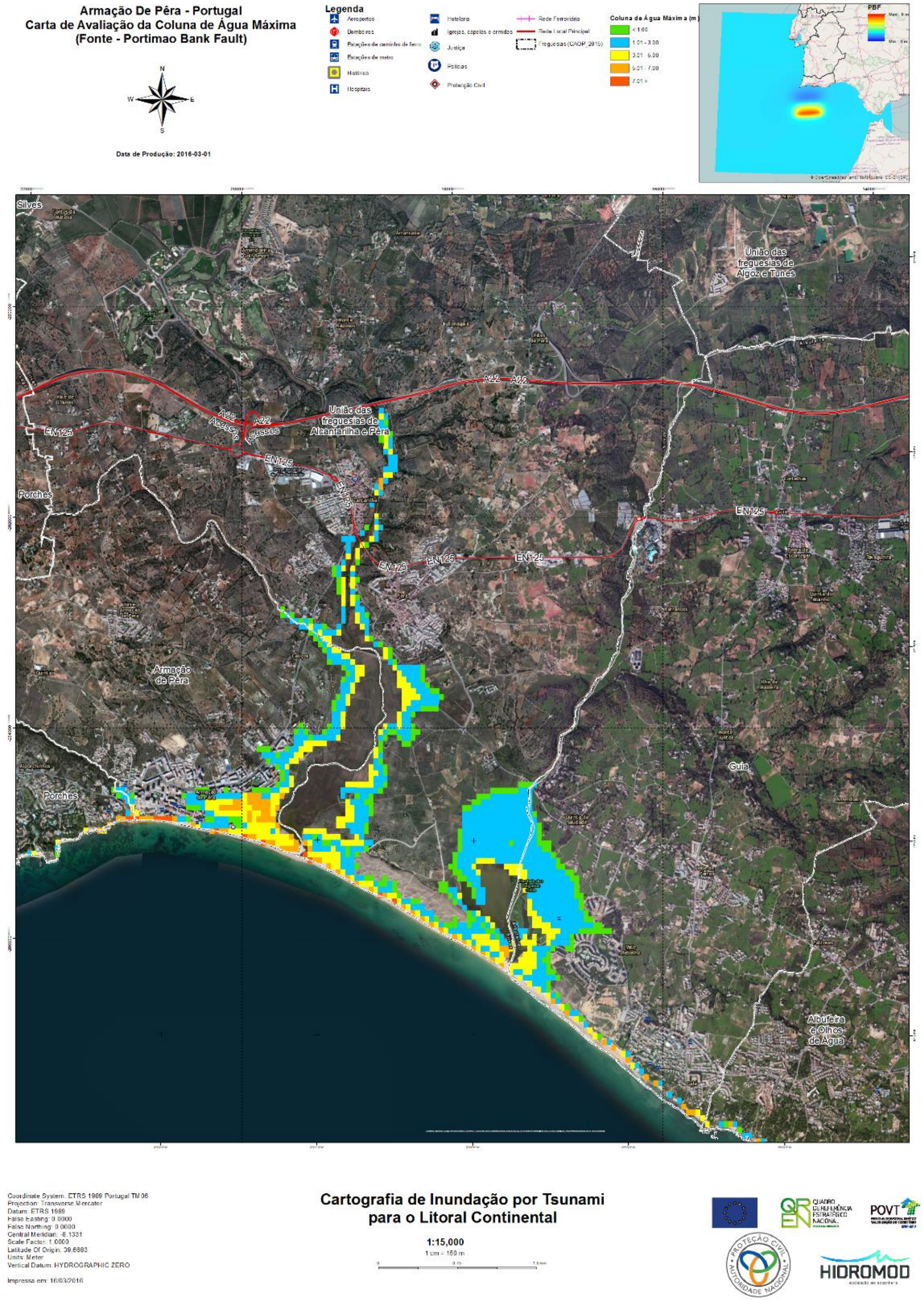
Maximum Water Column

Example: Armação de Pêra

Site Main characteristics

- ✓ *Major touristic area*
- ✓ *Long sandy beach's*
- ✓ *Restaurants Nearshore*
- ✓ *Camping sites*
- ✓ *Major resorts*

The maps display the flooded area above the imposed reference sea level

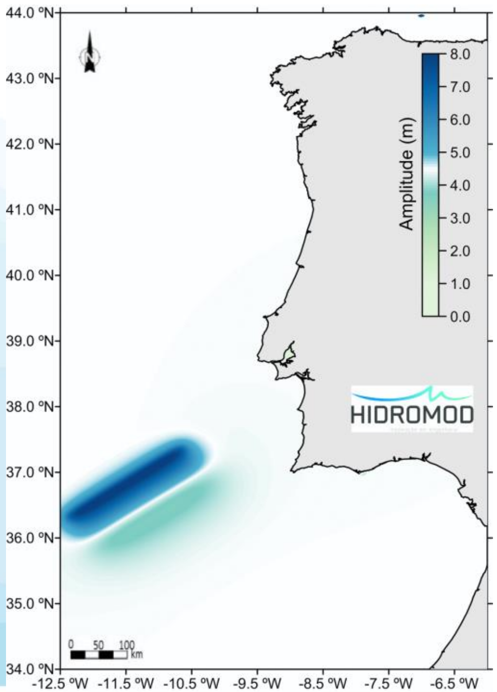


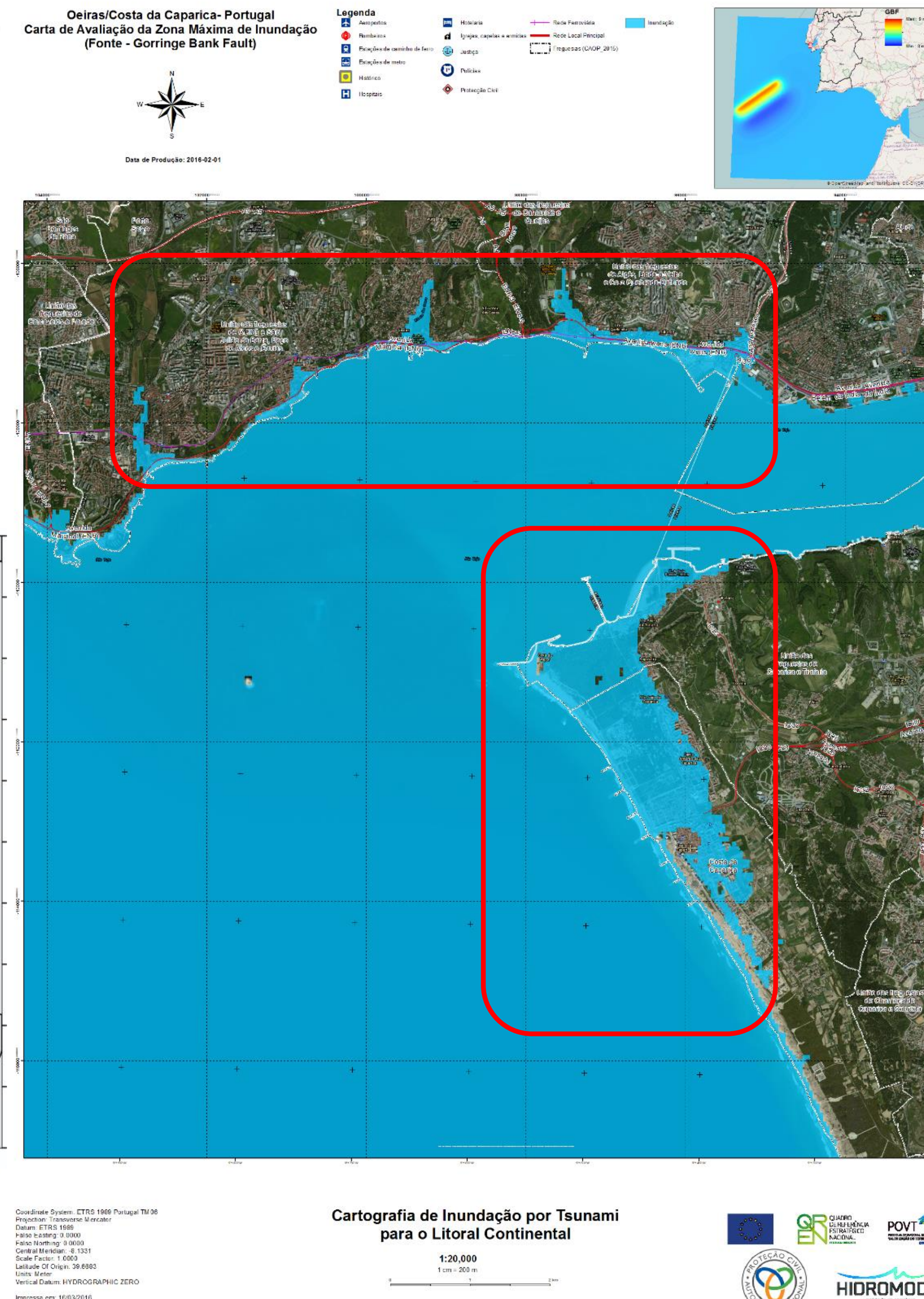
Maximum Inundation Maps

Example: Lisboa *(50 m resolution maps)*

Site Main characteristics

- ✓ Extensive coastline
- ✓ *Beach's*
- ✓ *Major roads to access Lisboa*
- ✓ *Marinas*
- ✓ *Camping sites*
- ✓ Major ship industries





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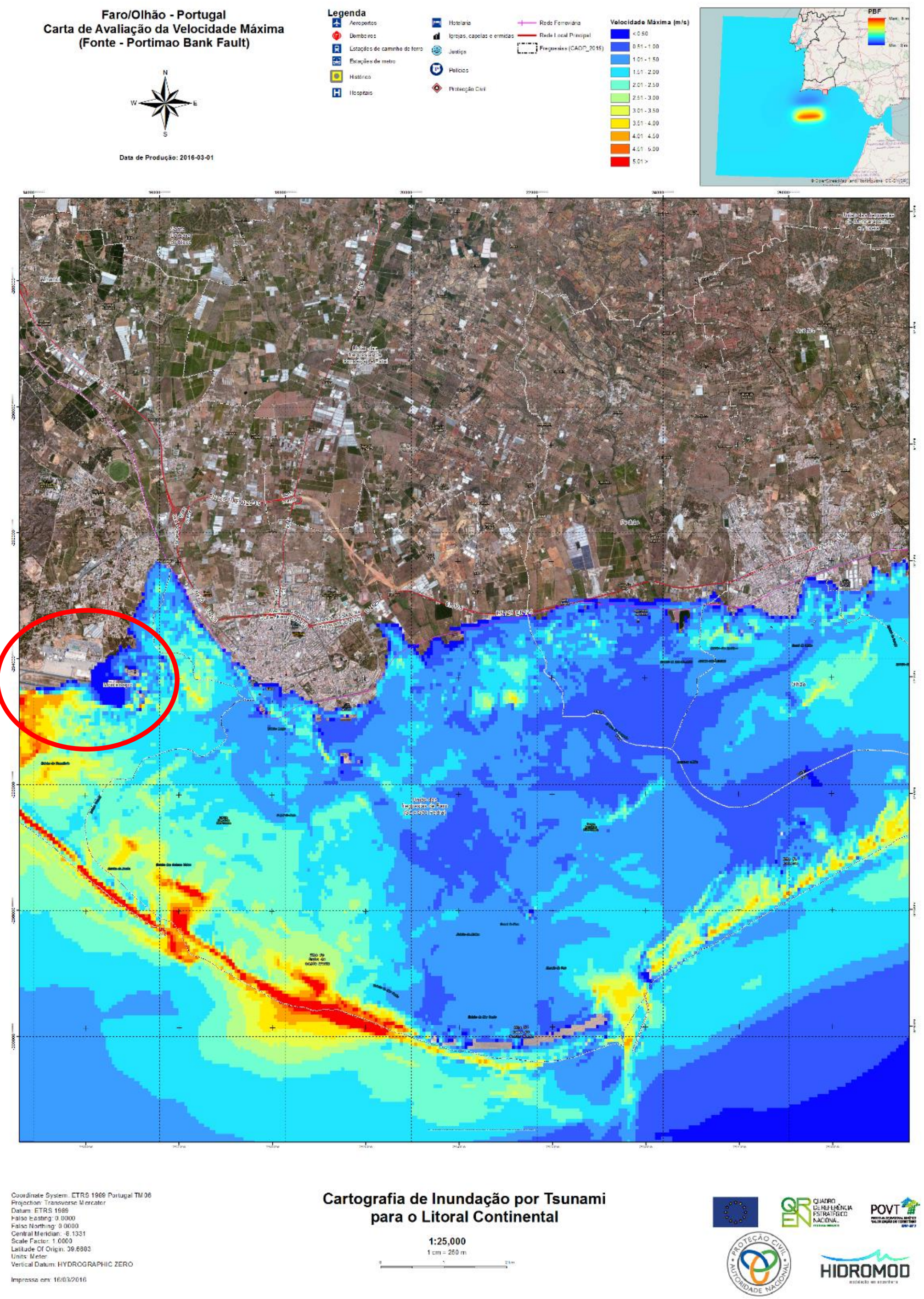
Maximum Velocity Maps

Example: Faro

Site Main characteristics

- *Major touristic area*
- *Long sandy beach's*
- *Restaurants Nearshore*
- *Camping sites*
- *Major resorts*
- *Airport*



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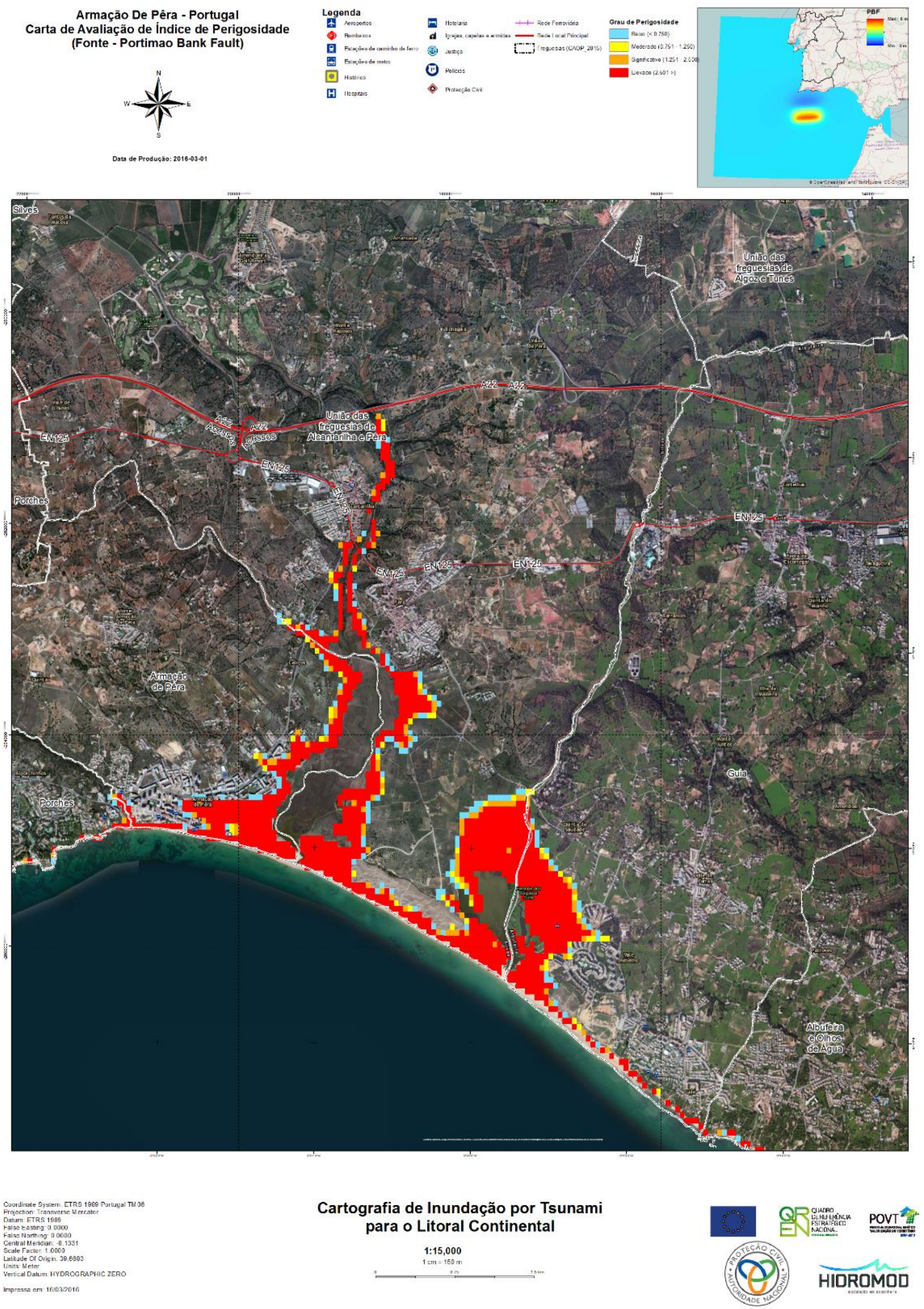
Maximum Hazard Maps

Example: Armação de Pêra

Site Main characteristics

- ✓ *Major touristic area*
- ✓ *Long sandy beach's*
- ✓ *Restaurants Nearshore*
- ✓ *Camping sites*
- ✓ *Major resorts*

The maps display the flooded area above the imposed reference sea level



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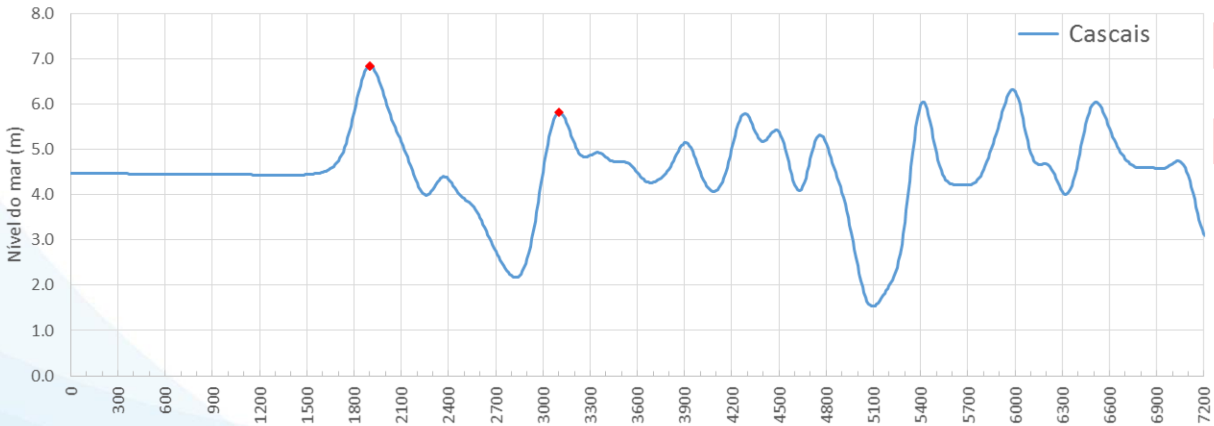
Water Level Time Series



Estação	Onda	HH:MM	Altura (m)
Albufeira	1ª Onda	0:47	5.41
	Máxima onda	1:35	5.91
Algés	1ª Onda	0:44	6.60
	Máxima onda	0:44	6.60
Armação de Pêra	1ª Onda	0:45	5.20
	Máxima onda	0:52	6.62
Aveiro	1ª Onda	1:03	4.93
	Máxima onda	2:36	5.41
Cadiz	1ª Onda	1:12	5.14
	Máxima onda	3:46	5.40
Cascais	1ª Onda	0:31	6.84
	Máxima onda	0:31	6.84
Costa da Caparica	1ª Onda	0:36	5.67
	Máxima onda	2:24	7.26
Costa de São Vicente	1ª Onda	0:20	5.53
	Máxima onda	0:43	5.59
Espinho	1ª Onda	1:13	5.32
	Máxima onda	3:24	5.69
Esposende	1ª Onda	1:04	5.07
	Máxima onda	4:52	5.24
Faro	1ª Onda	0:40	5.25
	Máxima onda	2:12	6.16
Figueira da Foz	1ª Onda	1:02	5.43
	Máxima onda	2:35	5.39
Huelva	1ª Onda	1:15	5.21
	Máxima onda	2:36	5.52
Lagos	1ª Onda	0:41	6.02
	Máxima onda	0:49	6.30
Vila Nova Milfontes	1ª Onda	0:31	5.75
	Máxima onda	1:23	6.40
Nazaré	1ª Onda	0:48	4.99
	Máxima onda	2:01	5.23
Oeiras	1ª Onda	0:37	6.35
	Máxima onda	1:03	7.12
Peniche	1ª Onda	0:46	4.98
	Máxima onda	4:21	5.58
Portimão	1ª Onda	0:43	5.66
	Máxima onda	0:50	6.59
Porto	1ª Onda	1:14	5.38
	Máxima onda	4:59	5.99
Porto de Sines	1ª Onda	0:31	6.41
	Máxima onda	0:58	6.69
Quarteira	1ª Onda	0:48	5.29
	Máxima onda	1:55	6.22
Setúbal	1ª Onda	0:33	5.57
	Máxima onda	1:56	6.69
Sesimbra	1ª Onda	0:24	5.57
	Máxima onda	0:52	5.83
Tavira	1ª Onda	0:53	4.80
	Máxima onda	2:21	5.50
Vale do Lobo	1ª Onda	0:46	5.09
	Máxima onda	3:25	6.59
Viana do Castelo	1ª Onda	1:09	5.14
	Máxima onda	5:00	5.24
Vila Praia Âncora	1ª Onda	1:05	5.07
	Máxima onda	4:20	5.22
Vila Real de Santo António	1ª Onda	0:57	4.93
	Máxima onda	3:14	5.59

HIDROMOD
modelação em engenharia

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Pressure correction method

- In a first step, the momentum equations are solved without the non-hydrostatic pressure terms, yielding an approximate velocity field in the horizontal directions denoted as $\tilde{U}^{n+1}$and $\tilde{V}^{n+1}$.

- A pressure correction term (*q*) is computed using a semi-implicit scheme (ADI). *q* can be given by the equation below, which follows a number of requirements, enumerated in Cui *et al.* (2012).

$$q(z) = \frac{2q}{3}\left[1 - \left(\frac{z+h}{H}\right)^3\right]$$

- $\tilde{U}^{n+1}$, $\tilde{V}^{n+1}$ and *q* are used to update the velocity field, as shown below.

$$U^{n+1} = \tilde{U}^{n+1} - \Delta t\left[\frac{1}{2}\frac{\partial q^{n+1}}{\partial x} + \frac{1}{2}\frac{\partial q^{n+1}}{H^n}\left(\frac{\partial \eta^n}{\partial x} - \frac{\partial h}{\partial x}\right)\right]$$

$$V^{n+1} = \tilde{V}^{n+1} - \Delta t\left[\frac{1}{2}\frac{\partial q^{n+1}}{\partial y} + \frac{1}{2}\frac{\partial q^{n+1}}{H^n}\left(\frac{\partial \eta^n}{\partial y} - \frac{\partial h}{\partial y}\right)\right]$$

- The vertical velocity can be expressed by the non-hydrostatic pressure by using the following equation:

$$w_\eta^{n+1} = \tilde{w}_\eta^{n+1} + 2\Delta t\frac{q^{n+1}}{H}$$