Finite Element Simulation of Earthquake Ground Motion with Coupling Tsunamis in Large Domains

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Objectives

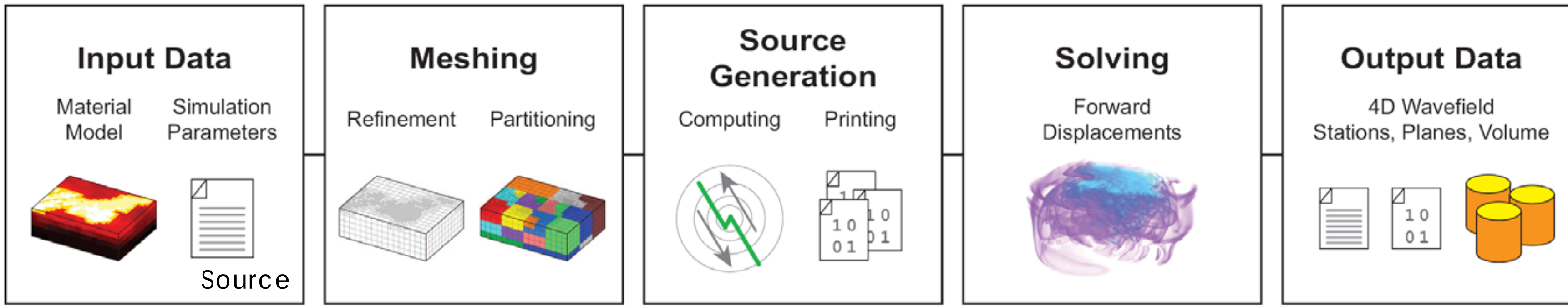
- Improve the capabilities of Hercules–the Quake-group parallel octree-based finite element software package for wave propagation simulations. Expand its capabilities to include the generation and offshore propagation of acoustic and tsunami waves triggered by seismic faulting.
- Apply the modified tool to the simulation of the 2011 Tohoku-Oki earthquake and tsunami.

PART - I

COUPLING EARTHQUAKE-TSUNAMI SIMULATIONS

Hercules

Our octree-based finite element tool for modeling earthquake ground motion* (Tu et al., SC2006)

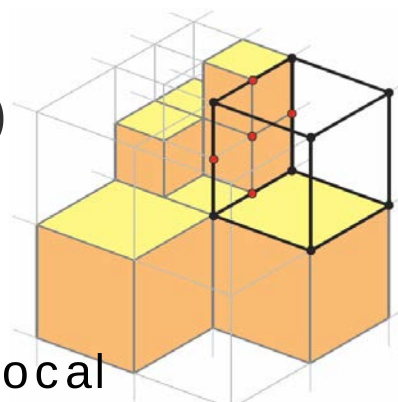


Hercules has been used for verification and validation studies (JB et al, GJI 2010; Taborda & JB, CiSE 2011, BSSA 2013,2014))

- **TeraShake (2005–2007) SCEC**
- **ShakeOut (2007–2009) SCEC+USGS**
- **Chino Hills (2008–2013) SCEC**
- **Volvi (2008–2010) Euroseis E2VP**

Octree-based FEM mesh

Mesh tailored to local shear wavelength



Berger, Young et al (1990s)

- and inventories of simplified building models (Isbiliroglu, Taborda & JB, Earthq. Spectra 2015)

Methodology

- We have chosen a Multi-System Approach

$$\ddot{p} - c_s^2 p_{,ii} = 0 \quad (1)$$

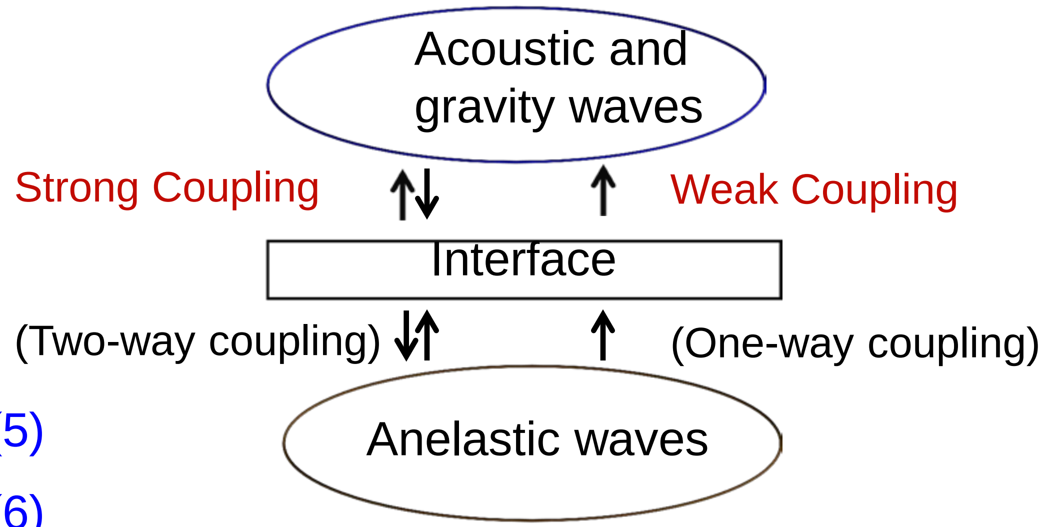
$$\frac{1}{g}\ddot{p} + p_{,i} n_i = 0 \quad \text{FS} \quad (2)$$

$$p^A_{,i} n^A_i - \rho^A \ddot{u}_i n^E_i = 0 \quad (3)$$

$$\sigma^E_{ij} n^E_j + p^A n^A_i = 0 \quad (4)$$

$$\rho_E \ddot{u}_i - \sigma_{ij,j} + f^B_i = 0 \quad (5)$$

$$\sigma_{ij} = \lambda u_{k,k}\delta_{ij} + \mu(u_{i,j} + u_{j,i}) \quad (6)$$



- Numerical Discretization (Applying standard Galerkin Method)

$$\mathbf{M_{dd}\ddot{d} + K_{\kappa} d + K_{\mu} d - R p^I = f_d} \quad (7) \quad \text{Solid Anelastic Domain}$$

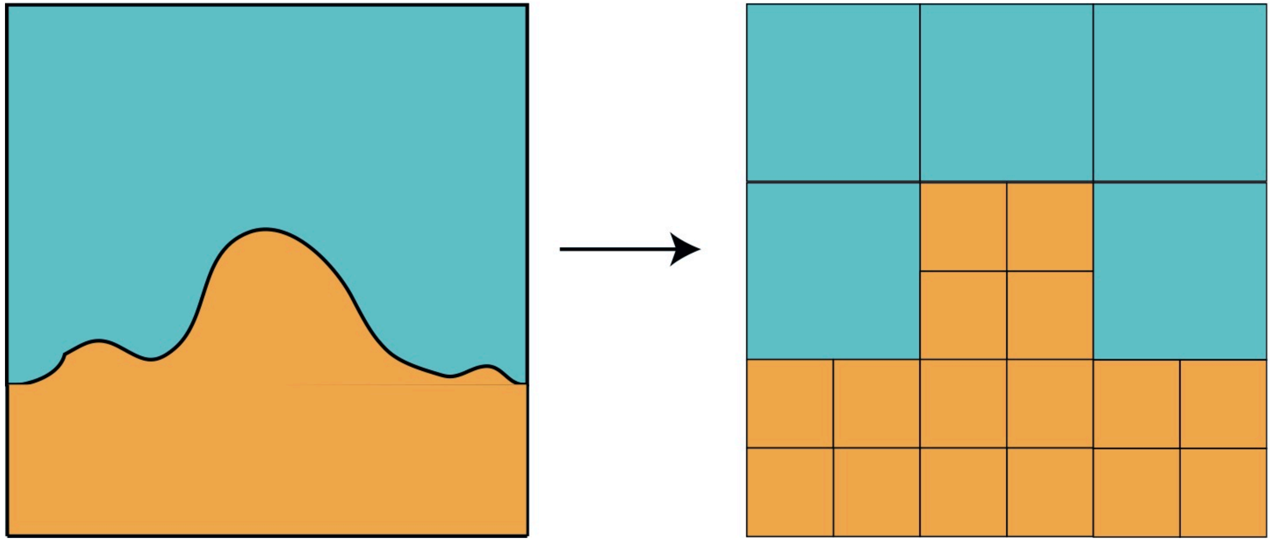
$$\mathbf{M_{pp}\ddot{p} + S\ddot{d}^I + K_{pp} p = f_p} \quad (8) \quad \text{Acoustic Domain}$$

- Requires a new solution scheme with additional message passing at the interface and appropriate computation schemes.

Interface Representation

DETECTION OF INTERFACE

- Detect bathymetry from seismic velocity model (no additional input).
- Acoustic domain in seismic velocity model is assigned zero shear wave velocity.
- Approximate the sea-solid interface region using cubes. (Same element scheme as for solid interfaces).

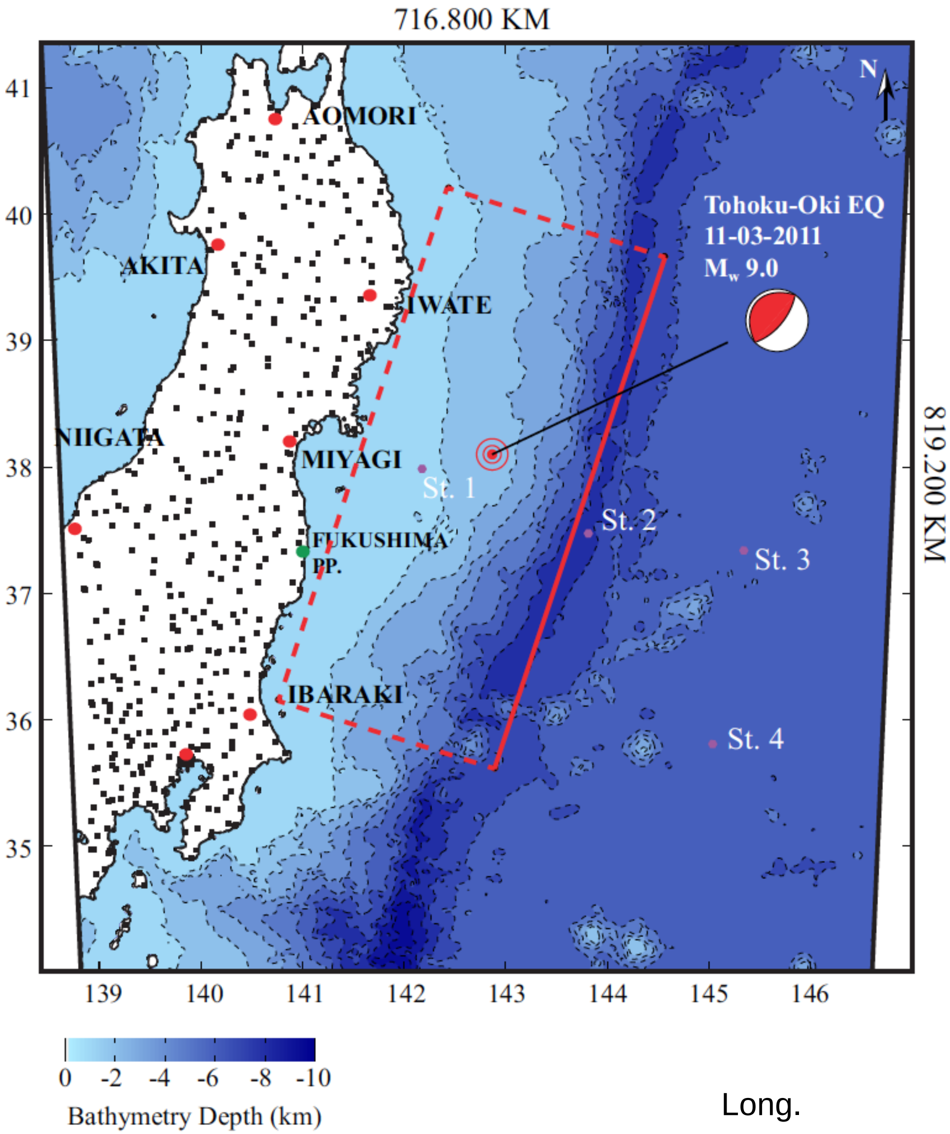


PART - II

2011 TOHOKU-OKI EARTHQUAKE AND TSUNAMI (3D)

Case Study

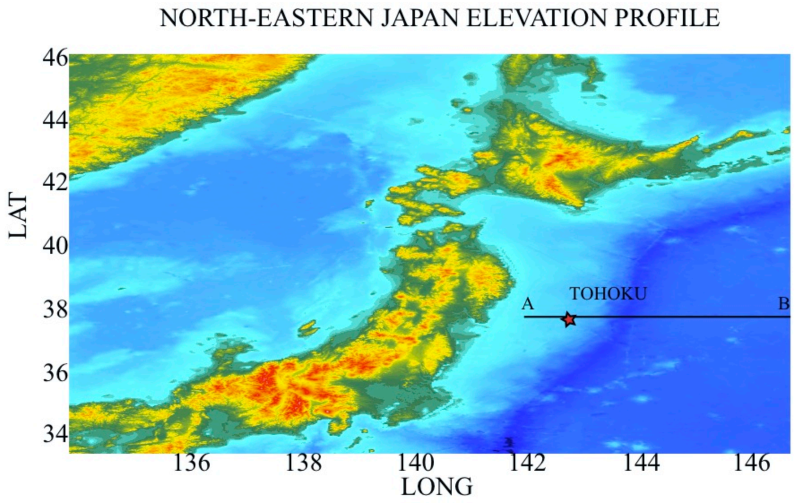
2011 Tohoku-Oki Earthquake and Tsunami



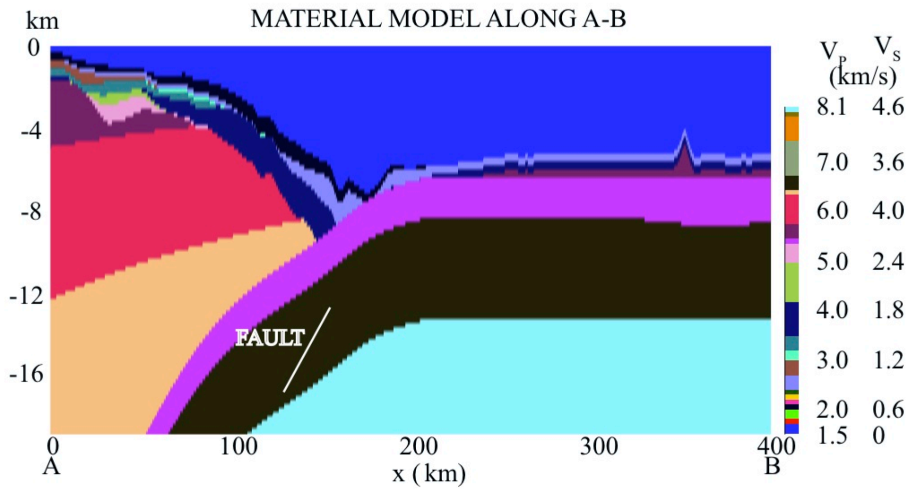
Long.

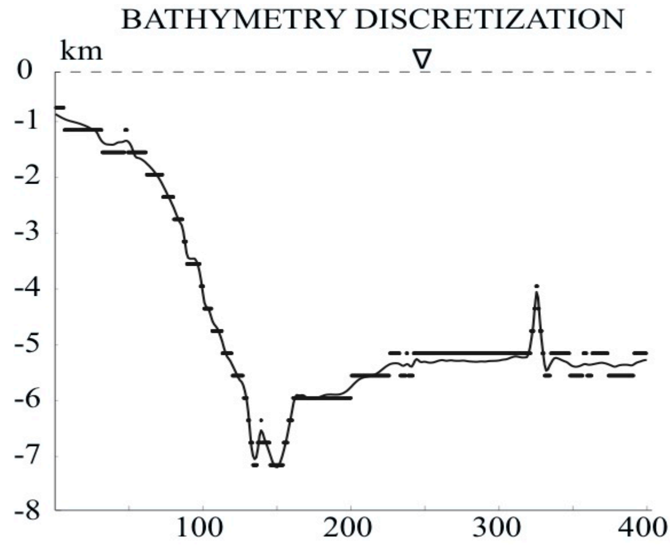
- A megathrust, subduction zone earthquake that generated tsunami waves.
- M_W = 9.0 – Fourth largest earthquake within the last 100 years.
- There are 467 stations in the region (K-net, Kik-net).

3D TOHOKU-OKI SIMULATION



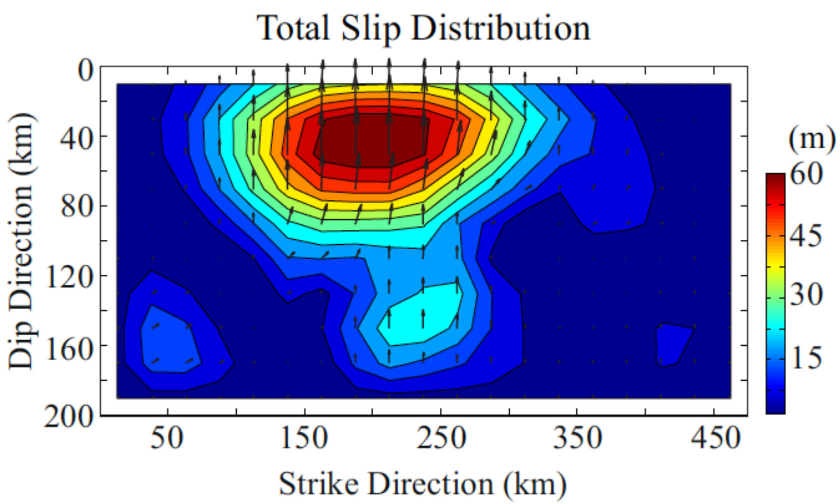
- Tsunami waves were observed predominantly in the E-W direction.
- 2D Cross-Section is taken along A-B (subduction zone) .

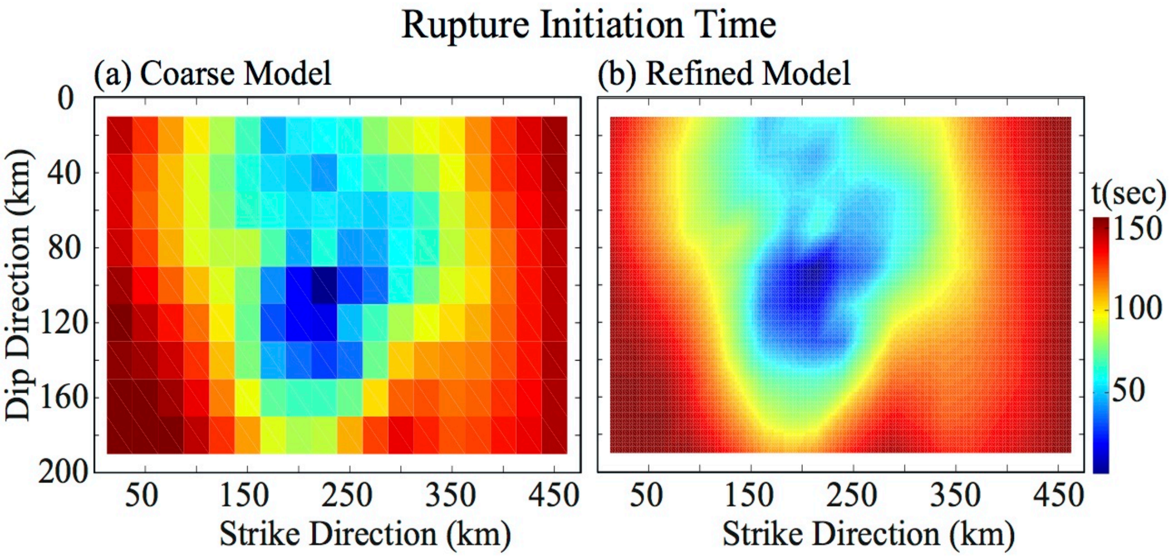




Notice horizontal and vertical scales are different

Case Study – 2011 Tohoku-Oki Earthquake
Source Model

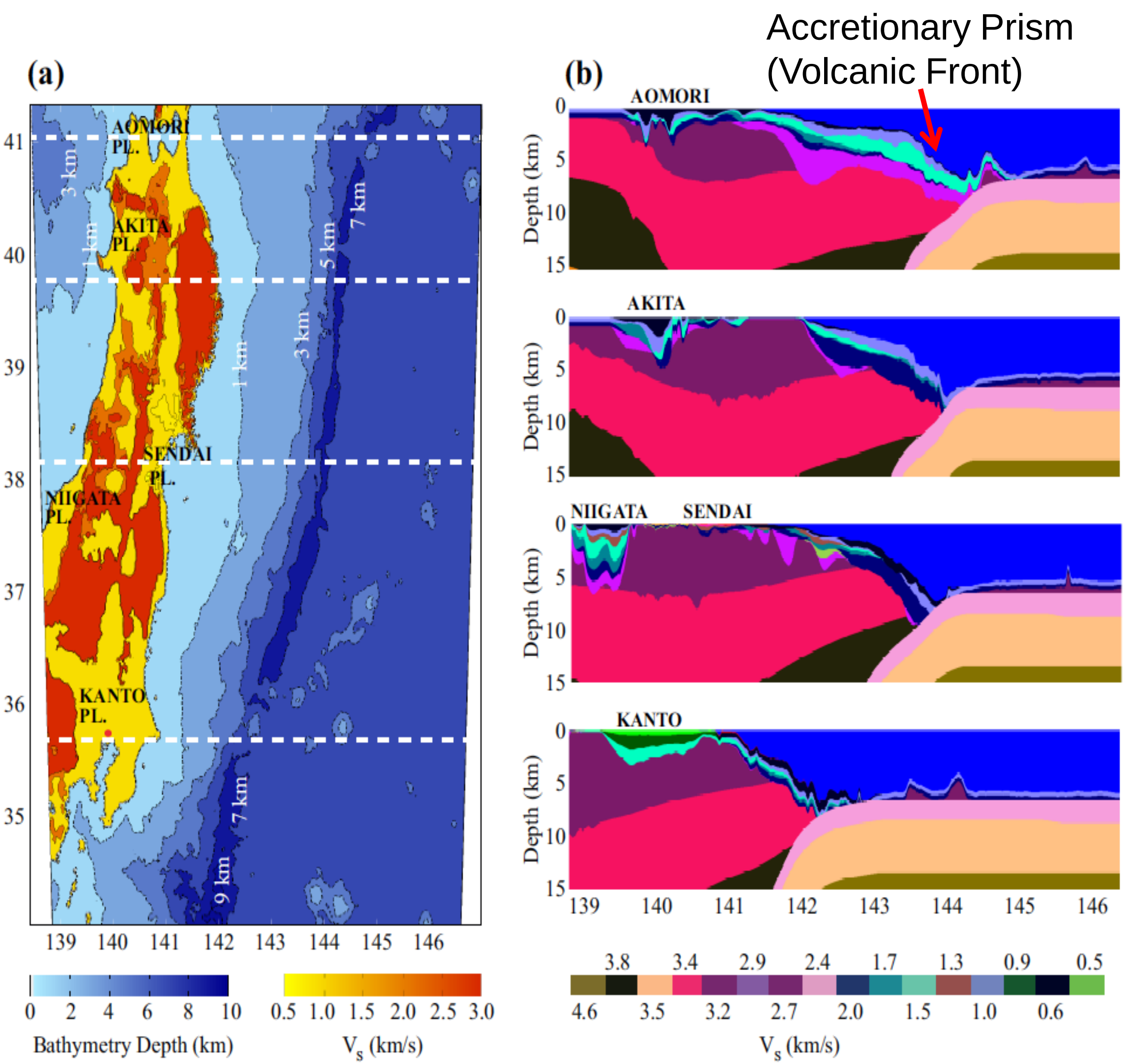




- Source model by Shao et. al. (2011)
- Smoothen rupture initiation time using triangular prism shape functions.
- Multiple asperity rupture.
- First ruptures down dip.
- Second ruptures up-dip (max. slip occurs here with 60 m)

Case Study – 2011 Tohoku-Oki Earthquake

Seismic Velocity Model



- Velocity model in Long-Period Ground Motion Hazard Map report (2012) by NIED is used for the simulations.
- Computational area covers several sedimentary basins in Honshu.
- Aomori, Akita, Niigata and Kanto basins are deep but Sendai is a shallow one.
- The figure on the left shows the S-wave velocity distribution on the surface and bathymetry depth.
- The figure on the right shows the cross-sectional views of S-wave velocity distribution along the dashed lines.

Case Study – 2011 Tohoku-Oki Earthquake Simulations

SIMULATION PARAMETERS

Domain	
Length	819.2 km
Width	716.8 km
Depth	204.8 km
Temporal Resolution	
Simulation Δt	0.0045 s
Simulation time	1400 s
Number of steps	288,889
Spatial Resolution	
Maximum frequency	0.5 Hz
Minimum V_S	500 m/s
Points per wavelength	$8 \leq p < 16$
Minimum element size	100 m
Maximum element size	400 m
Number of elements*	686,508,844
Number of nodes	5,971,885,216
Number of dangling nodes	373,688,580

*The elements counted are triquadratic.

COMPUTATIONAL PERFORMANCE

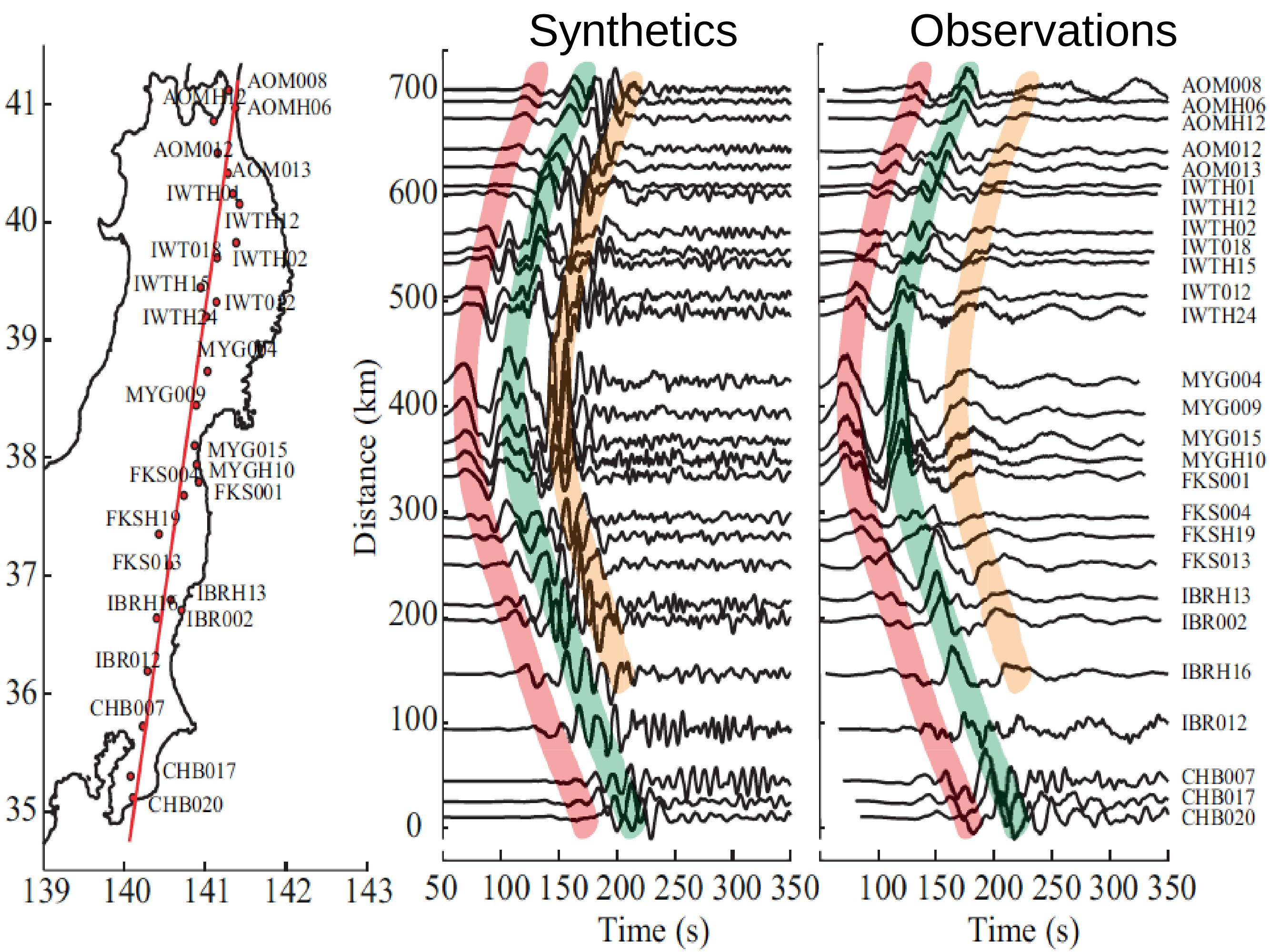
		hh:mm:ss	%
Number of cores	19,200		
Elements per core	35,756		
Total wall clock	78,321 s	21:45:20	100.0
Meshing	311 s	5:11	0.4
Source Generation	17,122 s	04:45:22	22
Solving	60,694 s	16:51:34	77
Compute	44,398 s	12:19:58	57
I/O transactions	654 s	10:54	1
Communication	15,624 s	4:20:24	19
Service Units (SUs)	417,600		

- Simulations conducted on Blue Waters (a petascale supercomputer).
- No significant difference observed in the computational performance of strongly and weakly coupled simulations.

STRONG GROUND MOTION
QUALITATIVE COMPARISON

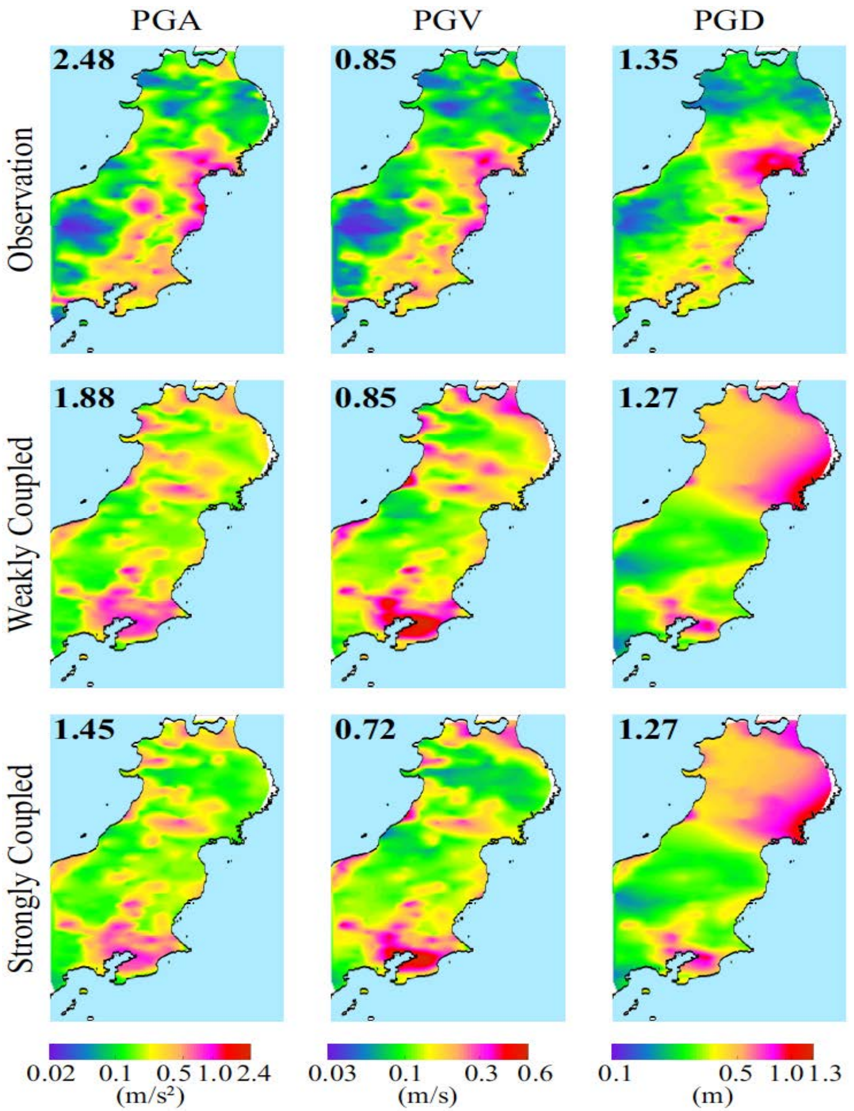
Qualitative Validation – Seismic Ground Motion
On-Shore Station Records

Displacement Time Histories (East-West)
Period range of 2-65 s

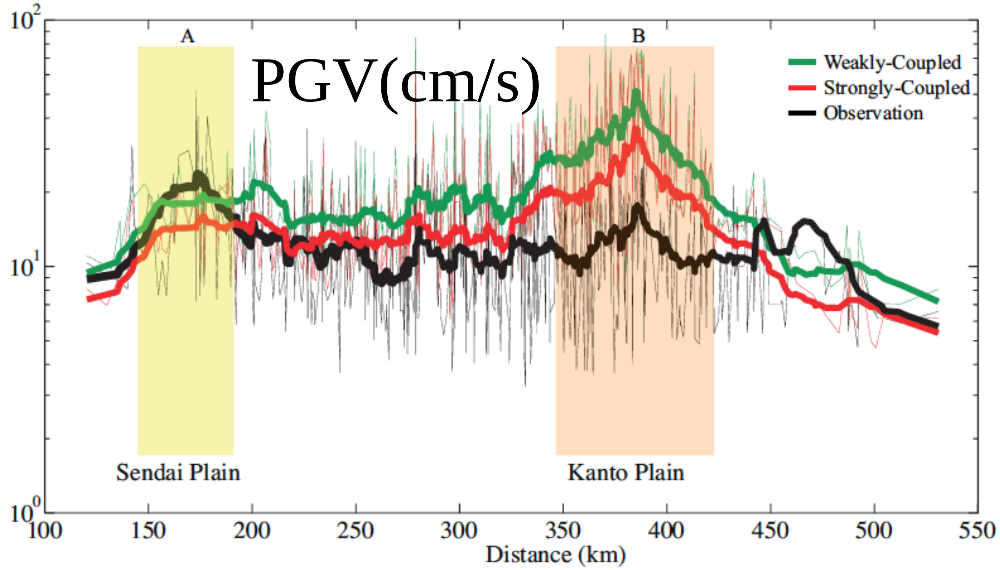


- Stations on a line extending from Aomori to Chiba prefecture (parallel to the strike direction of the fault).
- Synthetics capture the first two phases (direct waves).
- Third phase and the prolonged ground motion in the Kanto basin is overestimated.

Qualitative Validation
Intensity Measures (Peak Ground Motion)



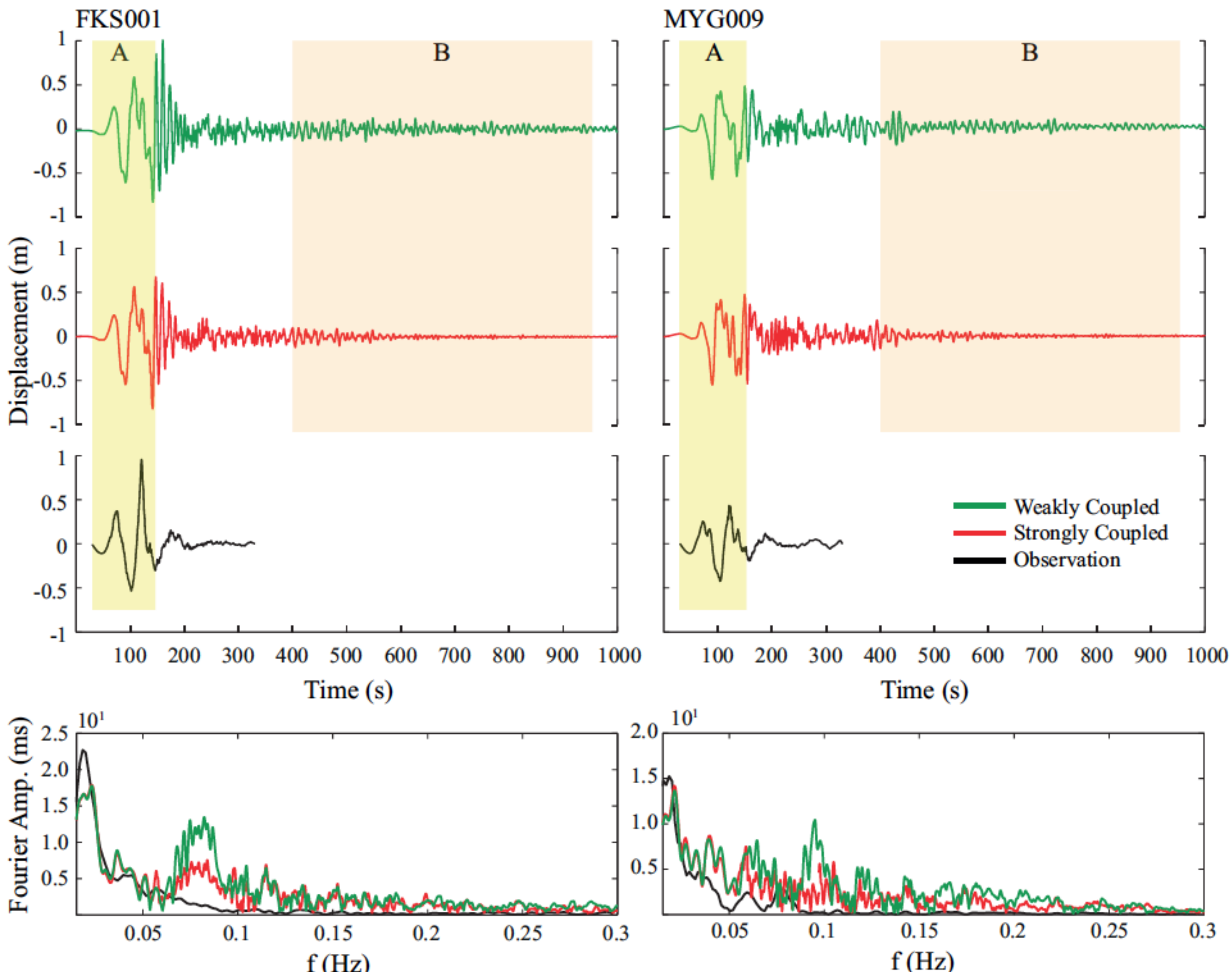
Seismic Attenuation Pattern



- PGV is overestimated especially in the Tohoku region and the Kanto basin.
- Introducing oceanic water layer reduces the misfit between the synthetics and the observations.

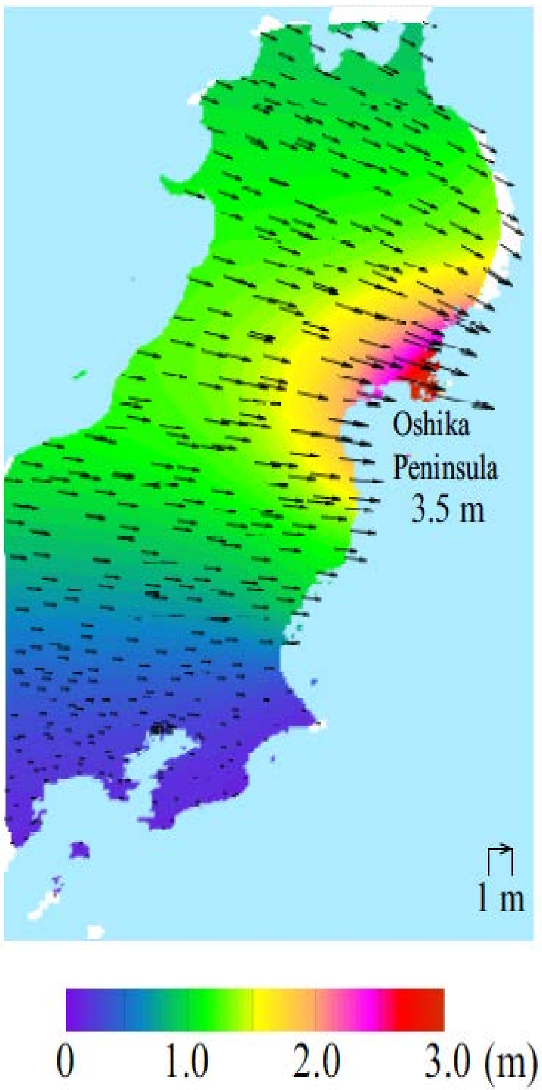
Qualitative Comparison

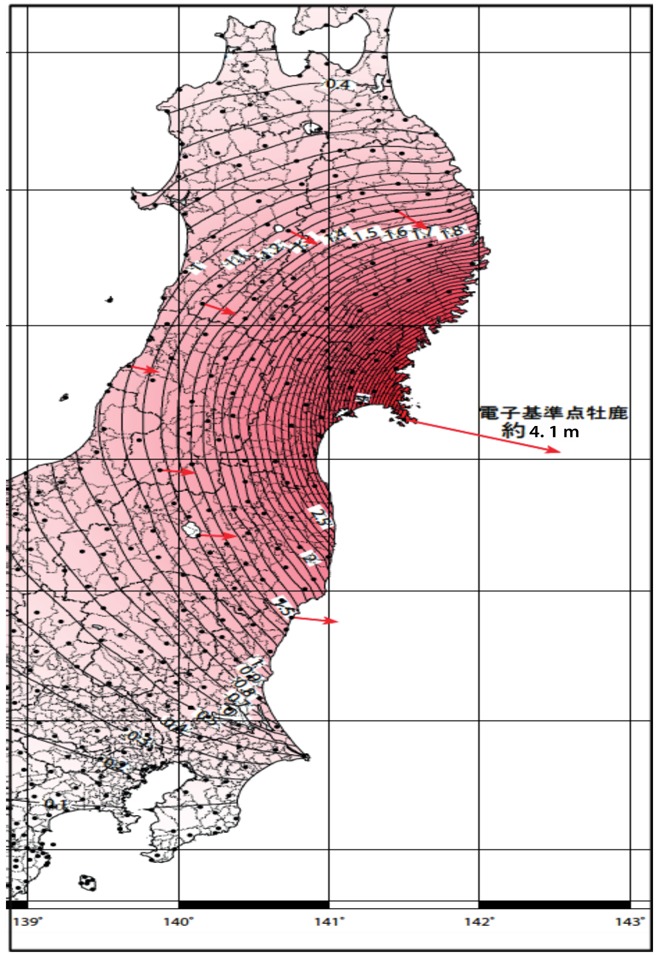
Strongly Coupled vs Weakly Coupled



- (A) Direct waves are captured with almost no difference. The waves from the deep fault show a better fit.
- (B) Strongly coupled case lowers the amplitude and ground motion duration. (Absorbing effect of oceanic water layer)

Quantitative Validation
Residual Displacement - Horizontal

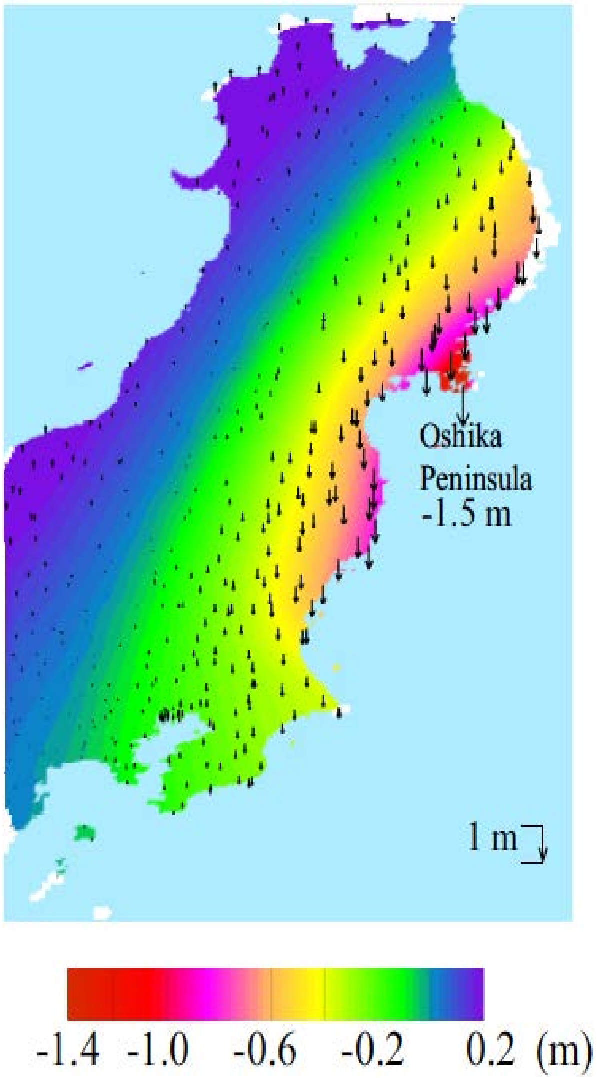


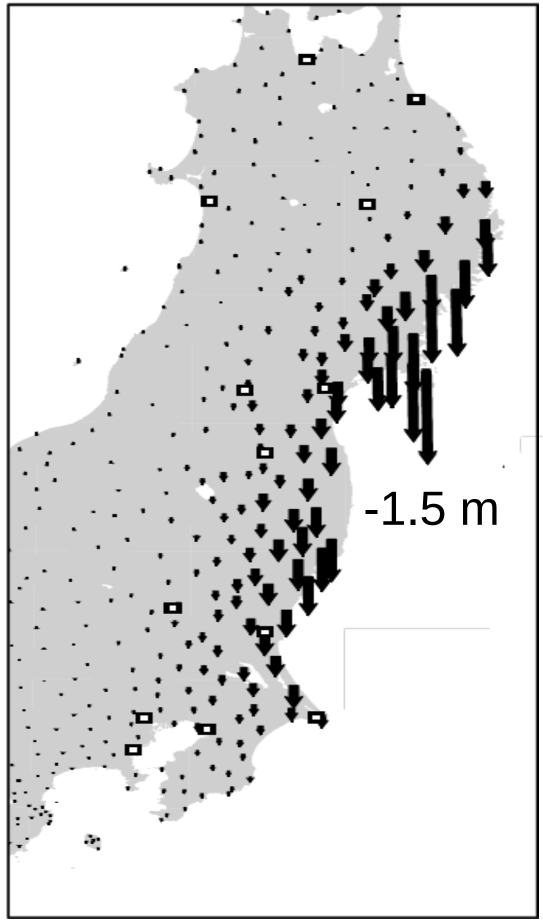


After JMA (2013)

- From GPS station records, maximum horizontal deformation is observed on Oshika Peninsula.
- Overall distribution is captured with some underestimation.

Quantitative Validation
Residual Deformation - Vertical





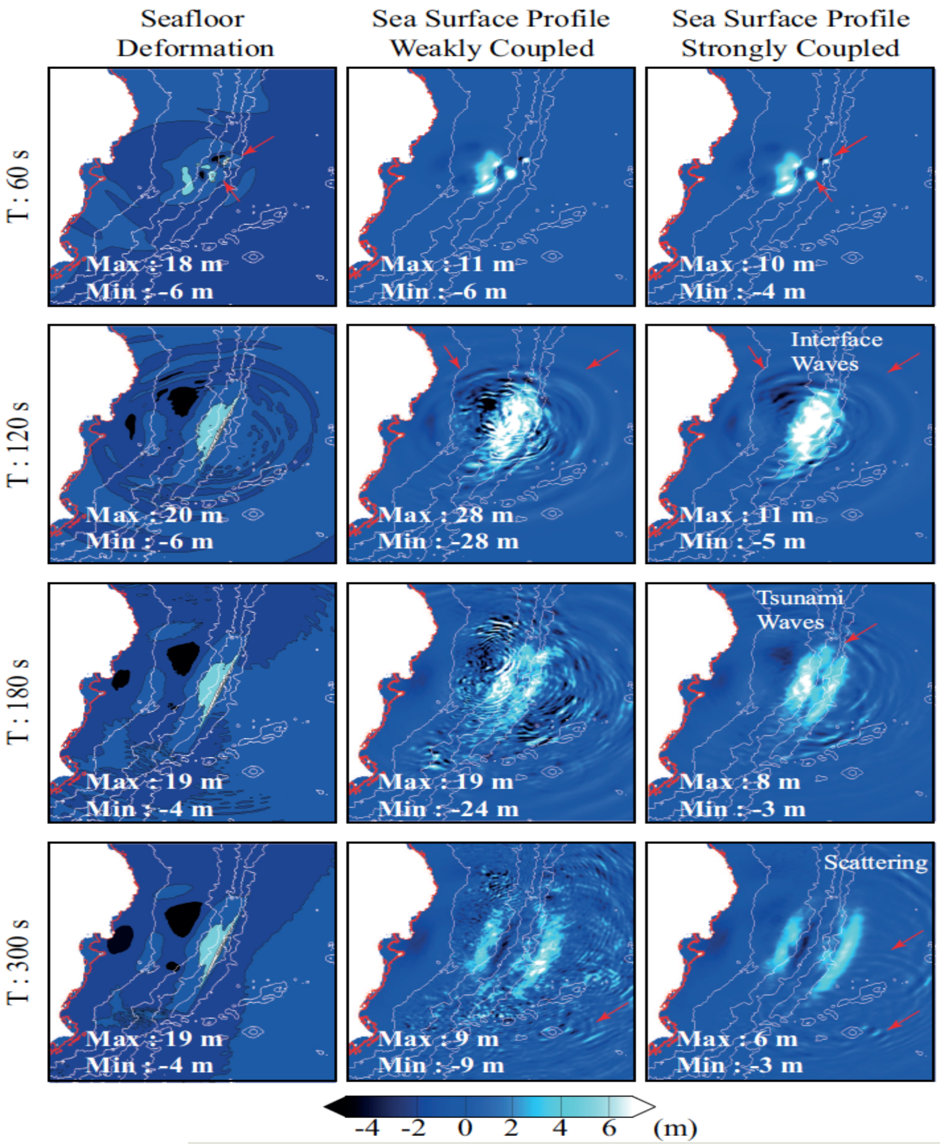
After Hashimoto (2013)

- From GPS station records, maximum vertical deformation is observed on Oshika Peninsula.

- Overall distribution is captured.

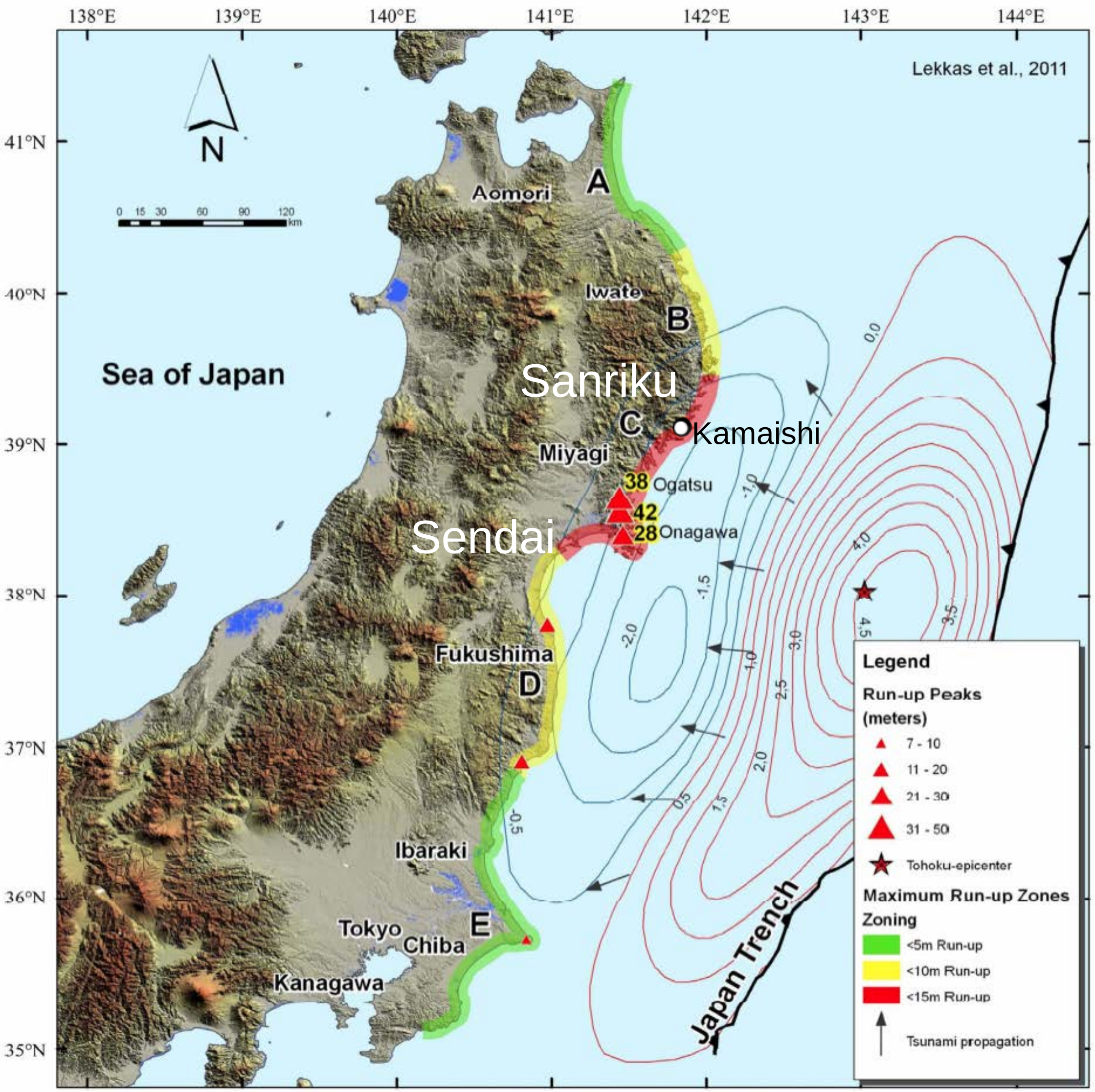
TSUNAMI WAVES

Qualitative Comparison
Tsunami Generation



- Sea surface deformation is quite different from the tsunami waves profile.
- First tsunami waves are seen after 3 min (180 s).
- Sea surface waves accompanying interface waves are captured (early warning purposes)
- Weak coupling overestimates acoustic fluctuations.

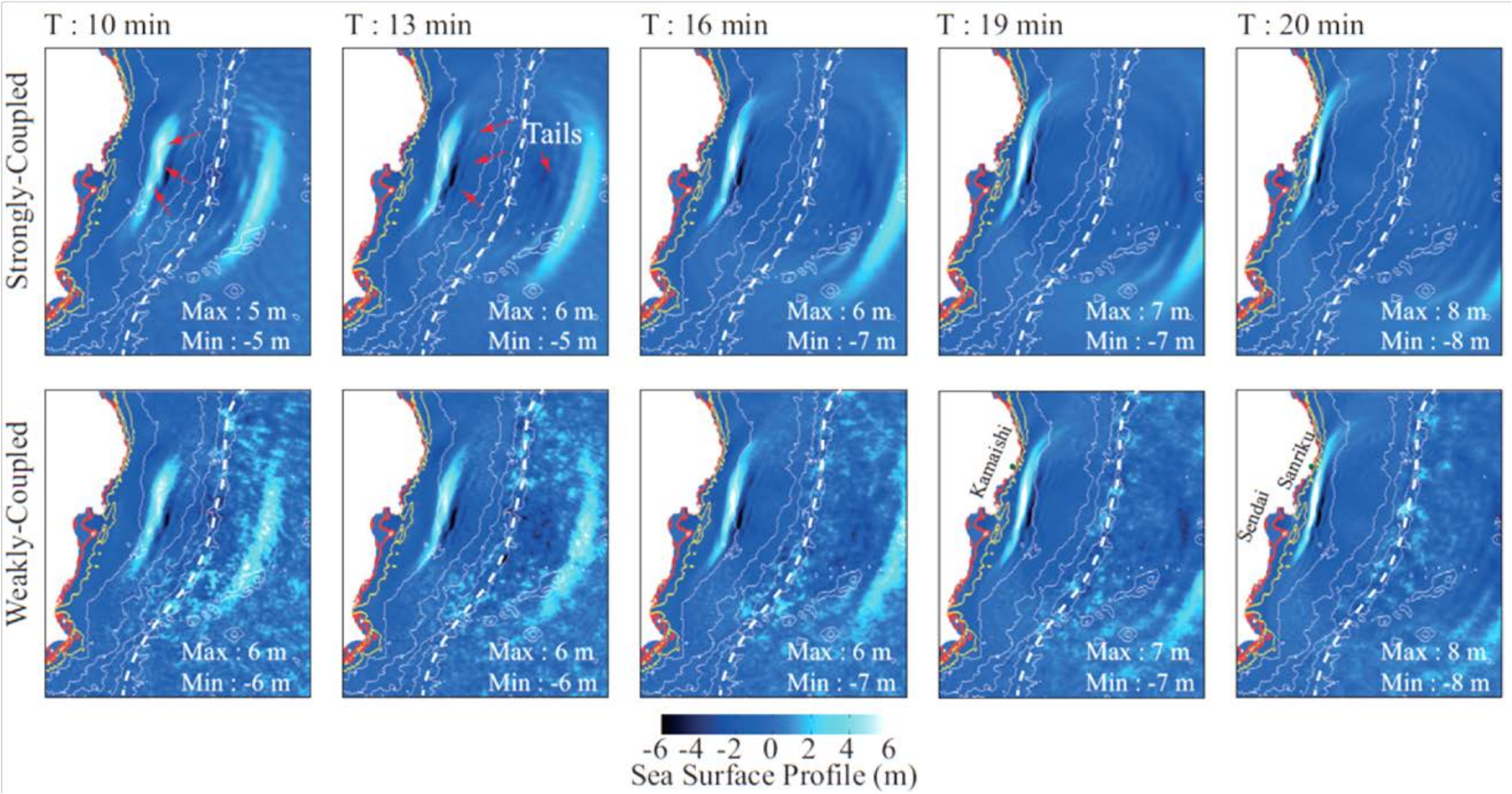
Qualitative Comparison
Tsunami Offshore Propagation



- Sendai and Sanriku coastlines were hit most by tsunami waves.
- First tsunami waves were observed around the city of Kamaishi.

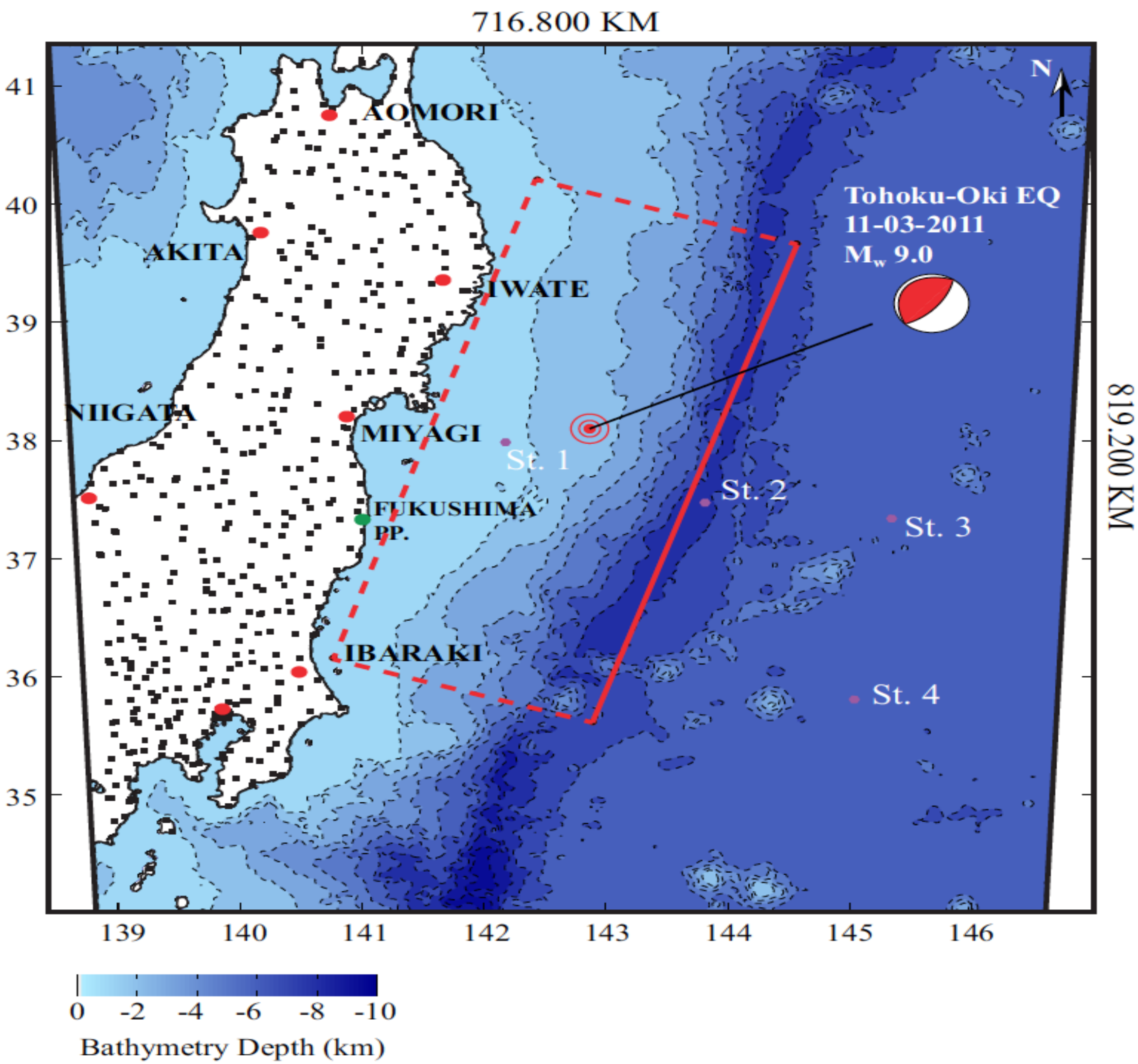
After Lekkas et. al. (2011)

Qualitative Comparison
Tsunami Offshore Propagation



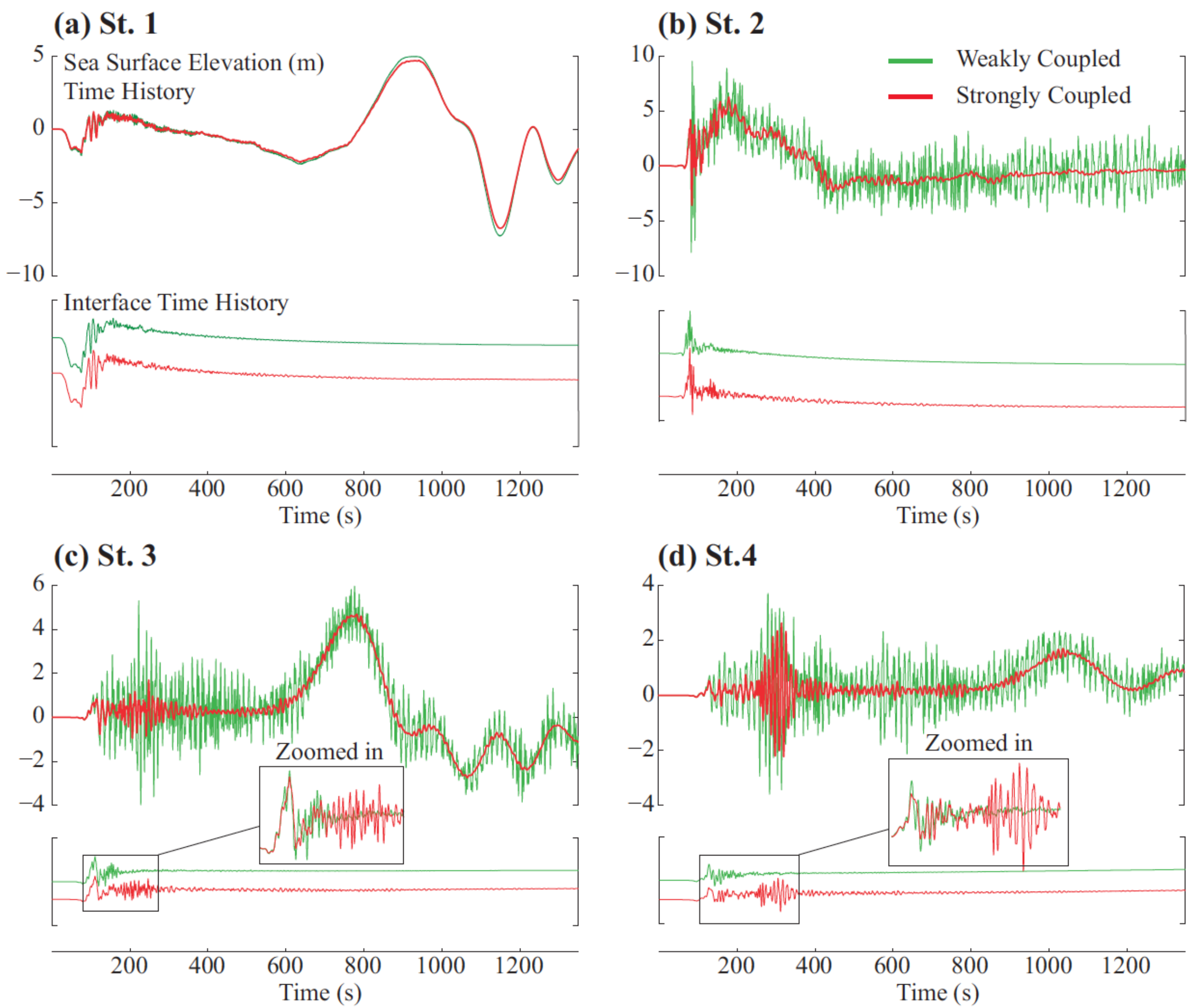
- To the west, tsunami waves heights increase and wavelengths decrease.
- Wave speed decreases as water depth decreases.

Sea Surface Elevation
Stations



Qualitative Comparison

Synthetics on Sea Surface



- Direct waves and interface waves are accompanied by identical sea surface elevation.
- Acoustic waves cannot travel upslope.
- Strong coupling leads to variation in the seafloor deformation histories (St. 3 and St. 4).

Case Study – 2011 Tohoku-Oki Earthquake
Conclusions

- Earthquake/tsunami simulation captures qualitatively and in some domains quantitatively the main characteristics of the ground motion and tsunami waves.
- Oceanic water layer has a strong absorbing effect on the surface waves, reducing the amplitude and duration significantly.
- Seismic attenuation patterns point to the poor modeling of the Q (Damping) in the material model especially in the accretionary forearcs.
- One-way coupling leads to an overestimation of the acoustic waves.

The End

Thank you

Anil, I wish you all the best always.