Linking geodynamic subduction models to self-consistent 3D dynamic earthquake rupture and tsunami simulations

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Motivation

3D dynamic rupture models of subduction zone earthquakes can account for complex structural variations of both fault and oceanic or continental crust. Due to the high inaccuracy and strong variations of material properties, fault strength and loading stresses along arc and depth, it is difficult to assign initial conditions to dynamic rupture models. A newly developed workflow bridges the spatial and temporal scales from seismology to dynamic rupture and links the outcome of geodynamic subduction and seismic cycling models to dynamic rupture (van Zelst et al., 2019). We use this approach to investigate how increasing complexity in terms of fault stress and strength, off-fault material and rupture dynamics impacts seafloor uplift and tsunami propagation and generation.

First, we use the 2D geodynamic and seismic cycling model as input for a 3D dynamic rupture model by extending heterogeneous along-dip material properties and stresses into the third dimension. Second, we show results of a 2D geodynamic model linked to a 2D dynamic rupture model including off-fault plasticity. Third, we show a newly developed fully-coupled 3D dynamic rupture-tsunami model in which acoustic and gravity wave propagation are directly coupled to seismic wave propagation and dynamic rupture. Earthquake rupture modeling and the fully-coupled tsunami modeling utilize SeisSol (www.seissol.org), a flagship code of the ChEESE project (www.cheese-coe.eu). SeisSol is an open source software package using unstructured tetrahedral meshes that are optimally suited for the complex geometries of subduction zones.

Linked models

1) 3D Geodynamic - Dynamic Rupture linking (linear elasticity)

- Initial total shear stress in dip direction taken from the 2D geodynamic model
- High sensitivity of earthquake dynamics to the dimensions of the nucleating weak region
- High slip rate and stress waves arrive up to downswath
- Seafloor uplift strongly depends on fault geometry as well as along arc material and stress variations

2) 2D Geodynamic - Dynamic Rupture linking (linear elasticity & off-fault plasticity)

- Off-fault plasticity results in:
  - Suppression of surface rupture and rupture propagation
  - Increased seafloor uplift (up to 10%)
- Convergence tests successfully performed

3) Fully coupled 3D dynamic rupture-tsunami model (Krenz et al., AGU 2019; Abrahams et al., AGU 2020)

- Direct coupling of wave propagation in water (acoustic wave propagation) with seismic wave propagation (elastic wave equation in linear elasticity)
- Modified free-surface boundary condition
- Linearized gravitational effect
- Limited burst of water layer in the elastic model of the 2018 Palu Swansea event that triggered a tsunami (Lotto et al., AGU 2019)

ChEESE - Center of Excellence for Exsauce in Solid Earth

- 13 Partners: includes academic and industrial institutions in 10 countries across Europe that are in charge of e.g. geophysical monitoring networks, hardware development, civil protection
- 10 Community flagship codes for the upcoming pre-Exascale (2020) and 2023 Exsauce (2023) supercomputers
- 4.8 million core years, 4 years of focused computational seismology (EXHAYPE, SALVIS, SEISSOL, SPECFEM3D)
- 2D tsunami modeling (T. Hysen, H. Hysen) 12 Pilot Demonstrations (PO)
- Model earthquake scenarios; seismotectonics, tsunami generation, source kinematics
- Evaluate the potential of different methods for tsunami wave generation and spreading
- Improve tsunami models for complex coastal areas

Methods

1-way coupling of subduction dynamics, seismology, earthquake dynamic rupture and tsunami models

- Fore-arc initial stress and earthquake rupture strength depend on initial conditions
- Model geometry and rheology as well as material properties and fault strength along arc and depth, it is difficult to assign initial conditions to dynamic rupture models
- Capture physical complexity of subduction evolution in dynamic rupture by simulating initial conditions of one slip event during the seismic cycling phase of the geodynamic model (provides all material properties)
- Model seaward displacement linked to tsunami model - tsunami sourced over entire simulation time
- Next step: tsunami model (Krenz et al., 2019) of very high spatial resolution into shallow water equation - efficiently models large scale horizontal as well as wave propagation and inundation

Outlook

- Evaluate effects of along arc variations of megathrust curvature, sediment content, and closeness to failure of the wedge on earthquake dynamics and initial plasticity in 2D dynamic rupture models constrained by seismology
- Change friction law from linear slip weakening to fast velocity weakening rate-and-state friction
- Dynamic earthquake rupture and tsunami simulation for the Hellenic Arc
- Knowledge on tsunami genesis and propagation essential for hazard estimation and tsunami warning
- Apply the method on realistic area in the Mediterranean Sea
- Compare the tsunami model described in this contribution with the state-of-the-art 3D seismic cycling and seismo-thermo-mechanical models
- Model several multi-physics DR EQ scenarios and varying topographical location at subducting slab, flat speed and resulting magnitude
- Present plausible tsunami scenarios and evaluate associated tsunami hazard
- Compare both, distributions, models and possible tsunami effects and tsunami waveforms generated all over around eastern Mediterranean
- Calculate and analyse non-linear inundation processes

References

van Zelst et al., 2019.

Zelst et al., 2019

Lotto and Dunham et al., 2015

Knowledge on tsunami genesis and propagation essential for hazard assessment, urgent computing and early warning forecast in the field of computational seismology (EXAHYPE, SALVUS, SEISSOL, SPECFEM3D). ChEESE - Center of Excellence for Exsauce in Solid Earth. 13 Partners: includes academic and industrial institutions in 10 countries across Europe that are in charge of e.g. geophysical monitoring networks, hardware development, civil protection. 

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