LINKED SUBDUCTION, DYNAMIC EARTHQUAKE RUPTURE, AND TSUNAMI MODELING

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ASCETE: ADVANCED SIMULATION OF EARTHQUAKE & TSUNAMI EVENTS
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How is it done?
- By joining three state-of-the-art, physics-based computational models

Why do it? To provide modeling methods in order to:
- Better understand the physical relationships between processes operating across the spatial and temporal scales of long term deformation, earthquake rupture and tsunami propagation
- Study the effects of a single subduction zone characteristics on earthquake & tsunami behaviors and of single earthquake characteristics on tsunami behavior
- Facilitate discussion of how to best link these processes across numerical models and study the influence of modeling choices on results

We hope many people adopt and develop these methods!
- 1 test case links subduction, earthquake & tsunami models
- 1 test case links earthquake & tsunami models (2 scenarios: high vs. low fault strength at the trench)
- We want to develop these into community benchmarks for linked modeling
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SUBDUCTION MODEL

Geodynamic-seismic cycle model of long-term subduction.

Begins with 1000 year time steps.

After reaching steady-state, the model transitions to seismic cycling with 5 year time steps and periodic slip events.

Materials are rate strengthening above 100°C and rate weakening below 150°C. Down-dip limit of seismogenic zone develops as viscous deformation begins to dominate above 350°C.
Yielding is controlled by the deviatoric stress.

Weakening is controlled by the deviatoric visco-plastic strain rate.

Stress changes during 1 slip event.
Earthquake rupture dynamics & seismic wave propagation are modeled with SeisSol

ADER-DG numerical scheme

Unstructured tetrahedral mesh with adaptive refinement

Verified for complex fault geometries, elastic and viscoelastic constitutive laws, as well as off-fault plasticity (Käser et al. 2007; Uphoff; Bader 2016; Wollherr et al., 2018)
2D Fault geometry  ➡️  3D Fault geometry

- The fault is not set a-priori in the subduction model, but must be pre-defined for the earthquake model. Fault locations are taken from the subduction slip event every 500 m in the dip-direction and at the depth of the maximum strain rate over the entire slip event.
- The 3D fault is built by copying these locations along strike.
- The resulting fault extends from 6 to 95 km depth. Dip increases with depth, ranging from 2° to 34° (average = 15°).

![Fault dip graph and 3D model](image)
LINKING SUBDUCTION TO EARTHQUAKE

- The material properties are mapped to be laterally uniform and from the onset of the subduction slip event.

- The subduction model assumes incompressible rocks with a Poisson’s ratio of 0.5. The earthquake model requires compressible materials, so we assign a Poisson’s ratio of 0.25. We calculate Lame’s parameter from Poisson’s ratio and the shear modulus.
LINKING SUBDUCTION TO EARTHQUAKE

2D Stress field  →  3D Stress field

- 2D effective Cartesian stress field from subduction model is mapped to 3D in the earthquake model, with all values constant in 3rd dimension. Off-fault plasticity can be implemented (Wollherr et al., 2018).

- Stresses taken from the onset of the subduction slip event.

- The pore fluid pressure is near-lithostatic at all depths ($\gamma = 0.95$).

Subduction model stress field  →  Tractions on the 3D fault in the earthquake model
LINKING SUBDUCTION TO EARTHQUAKE

- Cohesion mapped directly, except cohesion in sediments is increased to avoid nucleation here.

- The slip-weakening distance, $D_c$, is determined by equating the friction drop in the earthquake model to the friction drop in the subduction model.

van Zelst et al. (2019, JGR) “Modeling Megathrust Earthquakes Across Scales: One-way Coupling From Geodynamics and Seismic Cycles to Dynamic Rupture”

Cohesion and $D_c$ on the 3D fault in the earthquake model
LINKING SUBDUCTION TO EARTHQUAKE

Static friction is linked across models by equating the yield criteria ($P' = \text{effective mean stress}$):

- Subduction: $\tau_{s_{-}\text{SUB} \text{yield}} = C - \mu_{\text{SUB}} P'$
- Earthquake: $\tau_{s_{-}\text{EQ} \text{yield}} = c - \mu_{\text{EQ}} \tau_n$

- If $c = C$ and $\tau_n = P$, then $\mu_{\text{EQ}} = 0.05 \mu_{\text{SUB}}$. Assumption of $\tau_n = P$ holds at seismogenic depths.
- We also assume the dynamic friction coefficients follow this relationship.

Friction coefficients along the 3D fault in the earthquake model

Comparison of $\tau_n$ and $P$ along the 3D fault in the earthquake model
LINKING SUBDUCTION TO EARTHQUAKE

Nucleation occurs spontaneously in earthquake model due to relatively low static friction.

- In the subduction model, slip begins along the 2D fault at 40 - 43 km depth.
- In the earthquake model, a nucleation zone with radius = 1.5 km is set at 42 km depth.
- The minimum value at 40-43 km depth is applied in zone: $\mu_{EQ} = 0.018$, $\mu_{EQ} = 0.025$ outside zone.

All stress and frictional parameters along the 3D fault in the earthquake model
Dynamic Earthquake Rupture

Seafloor displacement above the fault

Slip on the fault

Spontaneous nucleation

0 s

Mw 9.0 earthquake

Slip rate

Uplift

SR

W

20.0

15.0

10.0

5.0

0.0

-5.0

25.0

17.5

10.0

2.5

-2.5
DYNAMIC EARTHQUAKE RUPTURE

Seafloor displacement above the fault

- Final peak uplift is 17 m at 240 seconds.

Slip on the fault

- No slip at trench
- Average slip is 42 m
- Max slip of 96 m occurs down-dip from trench
- Average rupture speed is 2.1 km/s, sub-shear relative to the nearby basalt (3.2 km/s)

Mw 9.0 earthquake
SCEC SEAS: LINKED SUBDUCTION, EARTHQUAKE, AND TSUNAMI

**LINKING EARTHQUAKE & TSUNAMI**

- Mw 9.0 earthquake
- Seafloor displacement above the fault
  - Final peak uplift is 17 m at 240 seconds.
- Maximum peak uplift of 29 m at 100 seconds.
The tsunami is modeled with SAM(oa)², which solves the depth-integrated shallow water equations with adaptive mesh refinement.

Efficient modeling of large scale horizontal flows and wave propagation with high accuracy.

Simple bathymetry setup with a flat seafloor above the earthquake source and linear beach.

Tsunami is triggered by the time-dependent perturbation of the discrete bathymetry over the entire length of the earthquake.

Maximum peak uplift of 29 m at 100 seconds.
The primary aim of this work is to develop linking methods, but it is informative to put the linked earthquake & tsunami model results into context by comparing them against observed events.

- Modeled earthquake magnitude and fault area are similar to the 2011 Mw 9.0 Tohoku EQ.
- Modeled slip is restricted at top of the fault, which slipped in the Tohoku EQ (Sun et al., 2017)
  - This is influenced by the linkage methods, in which we impose a higher cohesion in the sediments near the surface in the earthquake model to honor the rate-strengthening behavior in the subduction model.
- Mean modeled slip is 42 m and maximum is 96 m. This max slip is high relative to many estimates from slip inversions for the Tohoku EQ, but is similar to the highest maximum values out of a compilation of inversion models (Sun et al., 2017).
- Average modeled rupture speed is 2.1 km/s. Supershear rupture occurs locally near the hypocenter. Mean rupture speed for the Tohoku EQ is 2.5 km/s after 80 s (Ammon et al., 2011).
- Max modeled vertical displacement is 28 m at 100 sec and is away from the trench; average is 4 m at 100 sec. The vertical seafloor displacements from the Tohoku EQ are estimated to be ~10 m at the trench (Fujiwara et al., 2011). The modeled vertical displacements are high.
- The modeled tsunami has a max wave height of 15 m. A max wave height of 7 m was reached at Iwate Kamaishi-oki, while heights of 6 m were reached at several other locations (Japan Meteorological Agency, 2019). The height of the modeled tsunami wave is high.
Modeled slip magnitudes and seafloor uplift may be unrealistically high (e.g. relative to Tohoku). Alternative methods might improve this. However, the average stress drops are similar in the subduction slip event and the modeled earthquake. Alternative methods might alter this agreement.

**2D to 3D mapping:**
- We assume that the fault geometry, material properties, stress and frictional parameters are constant in the y-direction in the 3D earthquake model, a technically simple approach that likely does not reflect subduction zone characteristics.

**Poisson’s ratio, ν:**
- The subduction model assumes incompressible rock with \( \nu = 0.5 \), which is valid over long time frames, but not appropriate for dynamic earthquake rupture modeling. We choose \( \nu = 0.25 \) for the earthquake model. Using a larger \( \nu \) results in less fault slip (van Zelst et al., 2019). Alternatively, a material dependent \( \nu \) could be used.

**Static fault strength:**
- The relationship between the static coefficients of friction in the two models is solved for by equating their yield criteria and assuming \( P' = T_n' \) (van Zelst et al., 2019). This could be reconsidered.
- Rate-strengthening in the sediments is only approximated in the earthquake model.
- Bulk cohesion in the subduction model is not differentiated from on-fault cohesion in the earthquake model.

**Frictional weakening:**
- Coseismic weakening may be better captured in the earthquake model. Leave dynamic friction coefficients and slip-weakening distance un-linked? (e.g. Wollherr et al., 2018)
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2D tsunami model

seafloor displ. (earthquake-tsunami linkage)

2D subduction model

stresses and material properties (subduction-earthquake linkage)

3D earthquake model

Scientific computing
SUBDUCTION – EARTHQUAKE – TSUNAMI TEST CASE SUMMARY

Longterm subduction

Dynamic earthquake rupture

Tsunami

(using time-dependent displacements as source)

2D Fault geometry
2D Material properties
2D Stress field

3D Fault geometry
3D Material properties
3D Stress field

All stress and frictional parameters along the 3D fault in the earthquake model
RUNNING THE LINKED TEST CASE

Methods and Test Cases for Linking Physics-Based Earthquake and Tsunami Models

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SUPPLEMENTAL MATERIALS
osf.io/8qswg/

APPENDIX A: MATERIALS FOR RUNNING THESE TEST CASES
The materials required to run the earthquake and tsunami models involved in these test cases are provided on Google Drive at https://bit.ly/2INmM7q and later will be shared on www.zenodo.org. Outputs for the STM, earthquake and tsunami models also are provided. Details about these files and additional technical information for running both test cases are outlined in the following sections.

APPENDIX B: WHERE TO FIND THE COMPUTATIONAL MODELS
The STM code used to model long term subduction links geodynamics and seismic cycling. It is not publicly available.

SeisSol is used for the dynamic earthquake rupture models presented here. It is available at https://github.com/SeisSol/SeisSol along with compilation instructions, a user manual and examples. Information also is available at http://www.seissol.org.

samoa2 is used for the tsunami models presented here. It is available at https://gitlab.lrz.de/samoa/samoa.

APPENDIX D: MODELING DETAILS FOR THE SUBDUCTION-EARTHQUAKE-TSUNAMI TEST CASE

D1 The seismo-thermo-mechanical subduction model
The seismo-thermo-mechanical (STM) model has minimum resolution of 500 m in the subduction channel and a maximum resolution of 2000 m at the model edges. The final grid consists of 1654 x 270 nodes. A maximum of 51.6 million markers is used to track the materials.

We provide the section of the model output that is used as input for the earthquake model in a text file. This information is on a grid comprised of 1800 points in the x-direction and 1034 points in the z-direction at a resolution of 500 m. It covers a region that extends from x = -174.75 to 724.75 km and from z = 11.75 to -504.75 km. This region is shorter in the x-direction and longer in the z-direction than the subduction model domain. Values in the text file that are beyond the subduction model limits are copied from the closest depth and repeat. The region in the text file is also slightly larger than the region originally cut from the subduction model output, so values also repeat near the x-limits of the text file as well. This reflects the methods for linking a subduction slip event to a 2D SeisSol earthquake model, for which the text file must cover the entire earthquake model domain (van Zelst et al. 2019). Note that values at the limits of the provided text file do not affect behavior in this model. We provide these details only so that the interested modeler knows exactly what is provided. However, other physical models might require different procedures for porting the subduction model output to the earthquake model.

The 2D fault coordinates, determined after the slip event is complete, also are provided as a text file.
WE ALSO BUILT 2 EARTHQUAKE – TSUNAMI TEST CASES

- Scenario A has slip only below surface.
- Scenario B has slip to the trench.
- Depth dependent stresses
- Near lithostatic pore pressure
- Isotropic rock properties
- Slip-weakening friction

Dynamic earthquake rupture

Tsunami
(using time-dependent displacements as source)

Final fault slip

Sea surface height

Inundation

Final seafloor displacements
Island Gradually Sinking

Oceanic plate

Continental plate

Tectonics Observatory

YEARS 0 100 200
SUBDUCTION

2D long term geodynamic & seismic cycling model. *Provides initial conditions for the earthquake model.*

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EARTHQUAKE

3D rupture model of a single earthquake with seismic wave propagation. *Provides time-dependent, coseismic seafloor displacements for the tsunami model.*

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TSUNAMI

Non-linear, hydrostatic wave propagation and inundation model.

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SCIENTIFIC COMPUTING

Provides the highly optimized parallel algorithms and software that physics-based models of the necessary scale require.