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Dynamic Rupture Earthquake Simulations on complex Fault Zones with SeisSol at the Example of the Húsavík-Flatey Fault

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The Húsavík-Flatey Fault (HFF) in North Iceland is a 100 km long right-lateral strike slip fault connecting the Mid-Atlantic ridge in the north of Iceland to the Northern Volcanic Zone in Iceland. The HFF, which is composed of numerous fault branches, lies mainly offshore, but an onshore part passes through the town of Húsavík and merges farther east into the Theistareykir volcanic system (*Einarsson*, 2008). We present a 3D-model of the complete HFF which honors the complex fault geometry. Rupture dynamic simulations are performed on this model using SeisSol. Such simulations of earthquake source dynamics coupled to seismic wave propagation may add to a physics-based seismic hazard assessment for Húsavík as a significant tourism hub and future industrial center.

In the following, we will summarize the SeisSol methodology and the HFF model construction preceding the currently on-going dynamic rupture simulations.

SeisSol - an ADER-DG method for earthquake rupture processes and wave propagation

SeisSol is an open source software package developed at LMU Munich and optimized for high-performance computing at TU Munich (www.seissol.org). It is based on the arbitrary high-order derivative discontinuous Galerkin method (ADER-DG) and is able to efficiently simulate dynamic fault rupture coupled to seismic wave propagation providing insight into the poorly constraint earthquake source processes (*Käser & Dumbser*, 2006, *de la Puente at al.*, 2009, *Heinecke et al.*, 2014). The ADER-DG method combines high-order accuracy in space and time and low numerical dispersion with high computational efficiency. SeisSol uses unstructured tetrahedral meshes that allow to resolve complex geometrical features (*Dumbser & Käser*, 2006) such as the three-dimensional structures of Earth's interior, strong topography or complicated fault geometries in heterogeneous media. The mesh can be refined for a better resolution around regions of interest such as the fault and coarsened with distance away from the fault to reduce computational cost.

In order to simulate realistic earthquake scenarios and accurately resolve small-scale model features and dynamic shear failure at the rupture front, the high-frequency content of the wave field has to be resolved up to the relevant frequency range 0 to 10 Hz for engineering applications. This, however, leads to large meshes with up to hundreds of millions of elements and high computational cost. Recent optimization of the software (*Heinecke et al.*, 2014) allows efficient simulation of these large-scale scenarios on modern supercomputers such as SuperMUC located at the Leibniz

Supercomputing Centre in Garching near Munich (www.lrz.de/supermuc).

The software has recently proven to be highly scalable on current and future HPC infrastructure. It reached multipetaflop/s performance on some of the largest supercomputers worldwide, and was a Gordon Bell prize finalist application 2014 *(Breuer et al.,* 2014*; Heinecke et al.,* 2014*)* in a pioneering simulation of the 1992 M7.2 Landers earthquake. It is especially suitable to model earthquakes on realistic fault networks combined with modern friction laws and heterogeneous fault stress and strength conditions (*Pelties et al*., 2014).

A commonly used friction law solved in accordance with the background tectonic stress is the linear slip-weakening law (e.g. *Harris & Day*, 1993), which is applied in the here presented model of the HFF. It describes a linear relationship between the fault strength and the slip along the fault up to a slip-weakening critical distance.

Application to the Húsavík-Flatey fault

In order to perform dynamic rupture simulations along the HFF, the geometry software GoCAD followed by automatic meshing with SimModeler (Simmetrix) are used to create the unstructured tetrahedral grid of the HFF and its surroundings. The fault geometry is taken from *Magnusdóttir et al.* (2015).

In a first step, a slightly simplified model is built consisting of 9 fault branches aligned in the main strike direction of the fault system. In this model, it is assumed that the all sub-faults are locked at 6.3 km (*Metzger et al.*, 2011) and we assume a homogeneous subsurface structure.

In first simulations fault stress and strength are initialized based on SCEC (Southern California Earthquake Center) benchmark properties (http://scecdata.usc.edu/cvws/). The TPV8 benchmark describes a vertical right lateral strike-slip fault with a 3 x 3 km nucleation patch with higher shear stress (τ_{nuc}) than the surrounding fault and the following properties:

Table 1. Material and fault properties of the SCEC TPV8 benchmark

Density ρ	2700 kg/m^3
P-wave velocity v_p	5716 m/s
S-wave velocity v_s	3300 m/s
Cohesion c	1 MPa
Static friction coefficient μ_s	0.76
Dynamic friction coefficient μ_d	0.448
Slip-weakening critical distance D_c	0.5 m
Background normal stress σ_n	7378 Pa/m x depth
Background shear stress along strike τ	0.55 x σ_n
Nucleation shear stress along strike τ_{nuc}	c + 1.005 x μ_s x σ_n x depth
First Lamé parameter λ	29.403 GPa
Second Lamé parameter μ	29.41 GPa

In the following steps, the given parameters are adjusted to the case of the Húsavík-Flatey fault. Instead of assuming a normal stress perpendicular on the fault, the stress direction is rotated to the maximum compressive stress trending NNW-SSE (*Garcia et al.*, 2002, *Ziegler et al.*, 2016). Friction conditions will be adjusted considering regional thermal and geochemical conditions.

Furthermore, the velocity structure of the underground and depth-dependent stresses have to be adjusted.

The goal of our current models is to constraint realistic parameters and transfer them to a full-complexity model, in which all fault branches as well as topography and bathymetry are included. A crucial factor is the hypocenter location of a potential earthquake, which has to be prescribed. Different nucleation areas result in different rupture jumping scenarios and we will evaluate them in context of maximum magnitude and ground shaking in the Húsavík area.

Simplifications of our current model are the neglecting of a possibly varying locking depth of the fault from around 6.3 km in the eastern region of the HFF to a higher depth in the western part of the fault farther away from the volcanic system (*Metzger et al.*, 2011), a possible dip of the fault branches in the eastern and western ends together with a change of fault mechanism (*S. Jónsson*, pers. comm.) and the relationship to the volcanic systems of the Northern Volcanic Zone (e.g. *Maccaferri et al.*, 2013). Furthermore, correct stress values acting on the fault in normal and strike direction will be a major issue in order to simulate realistic rupture dynamics along the Húsavík-Flatey fault.

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