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Workshop on

Numerical Modeling of Earthquake Motions: Waves and Ruptures

2019 NMEM

Waves and Ruptures

Proceedings of the Workshop - Abstract Book

June 30 - July 4, 2019

Smolenice Castle near Bratislava, Slovakia

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PROCEEDINGS OF THE WORKSHOP

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ABSTRACT BOOK

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*Any opinions, findings, and conclusions or recommendtions expressed in this material are those of the author(s) and do not necessarily reflect the views of the National Science Foundation.

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CONTENTS

A B S T R A C T S

RUPTURE DYNAMICS AT THE INTERFACE BETWEEN A COMPLIANT LAYER AND STIFFER UNDERLYING HALF-SPACE

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We examined the sliding dynamics of a frictional interface between elastic solids. Our objective is to quantify sliding stability and rupture styles for a thin layer over half-space geometry with rate-and-state friction. This arises in many contexts, ranging from shallowing dipping subduction zones to ice streams (in particular, the Whillans Ice Plain (WIP), which advances via slow slip events). Specifically, we study the influence of layer thickness (H) on conditions for steady sliding vs. slow slip cycles vs. fast slip cycles, using both linear stability analysis and earthquake cycle simulations on a 2D anti-plane shear sliding of a compliant layer over a stiffer half-space.

Steady sliding with velocity-weakening rate-and-state friction is linearly unstable above a critical wavelength (Lc). For thin layers, such as the WIP, Lc is proportional to the square-root of H. But, as H is increased, Lc becomes independent of H and approaches to the well-known solution for sliding between two half-spaces.

The stability analysis provides insight into more complex situations, such as the nonlinear earthquake cycle dynamics of a nominally velocity-strengthening interface containing a velocity-weakening patch of width W. For small W, the patch slides steadily with the rest of the interface, and for large W the patch fails in fast earthquakes. Between these two limits, the patch exhibits slow slip events. We use our cycle simulations to map sliding style as a function of H and W, finding a trend that is consistent with the stability analysis. Overall this study demonstrates how the decreasing elastic stiffness associated with small layer thickness reduces the critical wavelength for instability, with important implications for rupture dynamics in thin layer geometries.

HOW 3-D FAULT GEOMETRY CONTROLS DYNAMIC EARTHQUAKE RUPTURES? VALIDATE PHYSICS-BASED MODELS WITH RECENT OBSERVATIONS

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We have made systematic validation to develop physics-based models to reproduce dynamic rupture processes of recent large earthquakes. Our models basically consist of those of regional stress fields, 3-D fault geometries and fault frictions, considered in the framework of the dynamic rupture simulations. In order to become the models testable, we constrain the models based on preseismic data as far as possible, and compare the results of the forward modeling with the coseismic observations. The numerical consideration of the realistic 3-D fault geometry have been made it possible with the Fast Domain Partitioning Boundary Integral Equation Method (FDP-BIEM), which is the O(N**2) method for the fully dynamic problem in the elastic half space.

We have targeted several large and middle size earthquakes including the 2014 Northern Nagano earthquake (Ando et al., 2017, EPS), the 2016 Kaikoura (New Zealand) earthquake (Ando and Kaneko, 2018, GRL), the 2018 northern Osaka earthquake and the 2018 Hokkaido Eastern Iburi earthquake. In the case of the Kaikoura earthquake, we successfully reproduced the multi-fault rupture observed by InSAR and the strong ground motion records. We can also reproduce the locations of the rupture arrest on the obliquely oriented fault segments, as controlled by the fault orientations relative to the regional stress field.

Ando & Kaneko 2018, Dynamic rupture simulation reproduces spontaneous multifault rupture and arrest during the 2016 Mw 7.9 Kaikoura earthquake. GRL, doi: 10.1029/2018GL080550.

Ando, Imanishi, Panayotopoulos and Kobayashi, 2017, Dynamic rupture propagation on geometrically complex fault with along-strike variation of fault maturity: insights from the 2014 Northern Nagano earthquake, EPS, doi: 10.1186/s40623-017-0715-2.

FROM ROCK CONCERTS AND SOCCER MATCHES TO IN-SITU, NON-LINEAR EXPERIMENTS : A NUMERICAL STUDY OF EXTREME MAN-INDUCED GROUND VIBRATIONS

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There have been over last decades several examples of large ground vibrations caused by people gathering for special events: a rock concert in Ullevi stadium (Sweden) in 1985 generated strongly felt tribune vibrations, while there are more and more seismological recordings of goals in high stake soccer matches (for instance, the Barça "remontada" against PSG in 2016-17 Champion's league, or the vibration levels recorded by broad band networks in Croatia and France during the 2018 World Cup final). Such man-induced vibrations can be a concern for the design of stadium facilities, in case of coincidence between structural frequencies and man-made beating frequencies (around 2 Hz). The present work reports a numerical investigation about how extreme could be such vibrations at ground level. We use the discrete wavenumber approach to model the wave field generated by surface sources (corresponding to vertical forces) with an amplitude corresponding to the surface load estimated for jumping crowds. We consider a ground layering leading to resonant frequencies close to 1 to 2 Hz, and compute the ground motion at distances from a few tens of meters to one kilometer. The largest ground motion is found to correspond to the center of circular source sets, a beating frequency tuned to the Airy phase of Rayleigh waves, and an underground structure with significant velocity contrast and low damping. In such cases, for linear elastic soils, the ground displacement is found to possibly exceed several cm, while the velocity can reach several tens of cm/s at the very center of the circle. This series of results thus pave the way to investigations on the use of concentric, active surface sources that could be combined to perform in-situ measurements of soil non-linear characteristics.

EARTHQUAKE RUPTURE MODELING USING FINITE ELEMENTS METHOD: FRACTURING VS. RATE AND STATE FRICTION

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Modern geodetic and seismic observations indicate that most earthquakes result from unstable shear on quasi-planar faults, usually represented as shear cracks. Better understanding of shear crack development, propagation, and arrest can help us learn more about earthquake behavior. In earthquake fracture mechanics, both the inelastic yielding at the rupture front and the evolution of friction on the remainder of the slipping surface should be considered. Thus, crack and friction models of an earthquake source should be intrinsically coupled and used jointly, but there is currently no theory that incorporates both effects simultaneously to describe earthquake rupture. To develop such a theory, we study different friction and fracturing models using Finite Element software PyLith and Abaqus. In this work we mostly consider planar ruptures. We use Abaqus eXtended Finite Element Method to model dynamic brittle cracking (i.e. mode I and mode II cracks) and fracture propagation in an elastic material, and PyLith to model plastic yielding at the crack tip regions and apply different friction laws along the fault (i.e. static friction, dynamic friction, slip-weakening friction, rate-and-state friction). We then compare the specifics of rupture propagation (i.e. time to instability, traction, slip, and slip rate distributions along the fault throughout the simulation) using the two approaches: brittle cracking and frictional sliding. Preliminary results show similarities in rupture propagation into the initially locked sections of the fault for the two methods, provided we predefine the crack path to be planar in the cracking approach. These results provide more insight into the correlation between friction and fracturing theories for the case of earthquake ruptures.

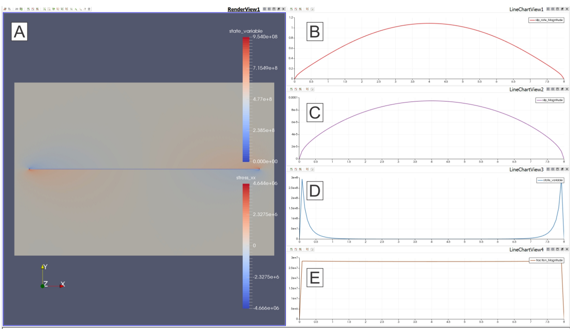

Figure 1. Rupture propagation along a planar fault with rate and state friction under shear loading conditions. A - horizontal stress distribution in the block, B - slip rate, C - slip magnitude, D - state variable and E - traction along the fault.

SOURCE CHARACTERISTICS OF THE EASTERN CARPATHIANS BEND (ROMANIA) 2016 EARTHQUAKE DOUBLET INFERRED FROM FULL WAVEFORM INVERSION AND CORRELATION TECHNIQUES

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The seismic activity in Romania is dominated by the subcrustal seismicity occurred in a very confined volume, placed at the bending of the Eastern Carpathians (Vrancea region). This is one of the most active intracontinental seismic areas in the World characterized by a predominantly compressive stress regime with significant tectonic deformation pointed out by two to four large earthquakes per century, producing hazard over extended areas. Recently, two moderate subcrustal earthquakes (Mw 5.5 and 5.6) occurred on 23 September and 27 December 2016 closely located and similar thrust fault plane solutions with the nodal planes oriented perpendicular to the Eastern Carpathians. This solution is less frequently observed compared with the preferred solution with the nodal planes NE-SV oriented, parallel to the Carpathian Orogen. The study aims to perform a detailed analysis of seismic activity within this region as well as an accurate determination of source parameters for the earthquake doublet (ED). To achieve these goals, we applied a multi-channel waveform correlation detector to the data recorded between July 2016 and February 2017 by a small aperture seismic array installed in the epicentral region while the source parameters were determined by running simultaneous methods based on spectral analysis and full waveforms inversion. Our results showed up to 15% new low magnitude events distributed around the ED indicating possible triggering effects. Possible differences in rupture velocity and stress drop are discussed, since the seismic moment is about 16% larger for the first event than for the second one and the rupture duration is rather similar. Also, how the difference in frequency content among the ED is reflected in fault heterogeneity.

OBSERVATION OF THE RAPID PLUNGE/ROLLBACK OF THE SLAB AND RUPTURE OF THE OVERRIDING PLATE AFTER AN INTERMEDIATE-DEPTH EARTHQUAKE : A POSSIBLE MECHANISM FOR THE AD 365 GIANT TSUNAMI EARTHQUAKE IN GREECE

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The devastating tsunami earthquakes of 2004 in Sumatra and 2011 in Japan came as shocks to the scientific community which had not expected the giant size of these events. The prevalent view of the existence of a characteristic earthquake cycle for a given region led to discard peculiar events from the distant past on grounds that they were too poorly known to be usable. The giant tsunami earthquake of 21 July 365 AD in Greece which uplifted part of Crete by $\sim$9m and devastated coastal areas of Eastern Mediterranean stands as one remarkable such event. How such a large earthquake occurred in a mostly aseismic subduction is an enigma. We show here that a sequence of unusual events in this subduction in 2008 sheds light on the mechanics of this giant event. Following a moderate rupture of the deep slab, the slab and overriding plate deformed in a few weeks over a zone $\sim$250km wide extending from $\sim$100km depth to sea bottom. These observations show that the slab can break, deform and plunge very rapidly over a huge area, producing the immediate rupture of the overriding plate. The chain of events seen in 2008 seems to contain many of the ingredients needed to produce a large tsunami earthquake in an aseismic subduction. We postulate that an acceleration of this chain caused by a large rupture of the deep slab led to the AD 365 event.

NUMERICAL MODELLING OF SEISMIC RESPONSE AT SITES WITH PRONOUNCED TOPOGRAPHY

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Concentrated earthquake damage at sites with pronounced topography has been reported in literature over last several decades, and attempts have been made to include topographic effects in earthquake hazard mitigation policies. Recent empirical studies conclude that the strong systematic amplifications observed at sites with pronounced topography are often correlated with ground motion directionality and primarily controlled by subsurface velocity structure, rather than the shape of the topography. However, a unique physical mechanism explaining the strong directional amplifications has not been discovered yet. In this contribution, 3D numerical modeling of local seismic response at a number of elevated (and instrumented) sites in Switzerland and Japan is presented. The joint effects of the terrain geometry and available velocity gradients are investigated by finite difference method. 3D seismic velocity models are developed by combination of measured shear wave velocity profiles and digital elevation models. Different methods of seismic wave-field generation for the site response analysis are tested and compared. Especially, the response based on a random forcing approach (i.e., ambient vibration response) is compared with the plane wave response. The synthetized ground motions are processed and compared with the observations. In particular, the directionality patterns obtained by polarization analysis are compared, as well as the synthetic amplification functions are compared with the empirical ones relative to a well-defined reference rock profile. The origins of the observed directionality are discussed.

NUMERICAL SOURCE MODELING OF INTERMEDIATE-DEPTH EARTHQUAKES IN SUBDUCTION ZONES

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The physical mechanisms that generate intermediate-depth earthquakes (70-300 km) within subducting slabs are not well understood, because the processes that enable shallow earthquakes are prohibited at extremely high temperatures and pressures. Furthermore, the data available from these earthquakes are scant in comparison to data for shallow earthquakes. Seismological studies of intermediate-depth earthquakes primarily focus on analyzing data assuming a very simple source model, but large intermediate-depth earthquakes have been shown to have complex ruptures. We use the support operator rupture dynamics code (SORD) to obtain more accurate models of the source processes of large intermediate-depth earthquakes, and to calculate stress drop and radiated energy, to compare with source scaling relations determined from small to moderate earthquakes extrapolate to larger magnitudes. We compare results obtained from kinematic and simplified dynamic inversion of the 2001 M6.7 Geiyo earthquake and the 2006 M6.4 Oita-Chubu earthquake in the subducting Philippine Sea Plate, and examine the sensitivity of spectral properties to assumptions about the source, such as whether or not the rupture is crack- or pulse-like. We thus aim to better constrain the physical mechanisms of intermediate-depth earthquakes, and ultimately better assess the hazards of these rare, but often damaging earthquakes.

PHYSICS OF THE DAMAGING GROUND MOTION IN THE VALLEY OF MEXICO ON SEPTEMBER 19TH, 2017 (MW7.1)

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Built-up on top of ancient lake deposits, Mexico City experiences some of the largest seismic site effects in the world. The M7.1 intermediate-depth earthquake of September 19, 2017 (S19) collapsed 43 one-to-ten story buildings in the city close to the western edge of the lake-bed sediments, on top of the geotechnically-known transition zone. In this work we explore the physical reasons explaining such a damaging pattern and the long-lasting strong motion records well-documented from past events by means of new observations and high performance computational modeling. Besides the extreme amplification of seismic waves, duration of intense ground motion in the lake-bed lasts more than three times those recorded in hard-rock a few kilometers away. Different mechanisms contribute to the long lasting motions, such as the regional dispersion and multiple-scattering of the incoming wavefield all the way from the source. Recent beamforming observations at hard-rock suggest that duration of the incoming field is significantly shorter than the strong shaking in the lake-bed. We show that despite the highly dissipative shallow deposits, seismic energy overtones dominating the ground motion from distant earthquakes can propagate long distances in the deep structure of the valley, promoting also a large elongation of motion. However, our results for the S19 earthquake indicate that the damage pattern in this case is most likely due to the propagation of the surface waves fundamental mode across the transition zone of the basin. Transduced and induced waves along the basin edge are thus responsible of the localized damage pattern.

PHYSICS-BASED RUPTURE MODELS FOR FAULT DISPLACEMENT ASSESSMENT OF SURFACE-RUPTURING EARTHQUAKES FOR NUCLEAR INSTALLATIONS

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Surface-rupturing faulting is usually expected from large earthquakes, but this phenomenon has been also observed in moderate earthquakes. The coseismic fault displacement associated to earthquakes can seriously compromise the safety of critical infra-structures located near faults, such as bridges, dams, pipelines, nuclear installations (NI) and nuclear waste repositories. The IAEA specific safety requirements (Site Evaluation for Nuclear Installations No.SSR-1, DS484) requires that the capability for surface faulting shall be assessed for the site of a NI. But current practices of fault displacement hazard assessments (FDHA) are in general very challenging and quite limited because recorded fault displacement data are very sparse, as such, at present very few empirical models with large uncertainty are available for this purpose. IAEA has already recognised this issue and currently is making the effort to implement the physics-based rupture modelling in practice for FDHA. These efforts have been discussed through different international working group activities, being the most outstanding two international workshops on Best Practices in Physics-based Fault Rupture Models for Seismic Hazard Assessment of Nuclear Installations (BestPSHANI) in 2015 and 2018. And currently we are writing an IAEA-TECDOC (Technical Document) on Probabilistic Fault Displacement Hazard Analysis (PFDHA) in Site Evaluation for Existing Nuclear Installations. In this TECDOC we are explicitly describing the use of physics-based dynamic rupture models for PFDHA. Here we discuss the feasibility of the use of Physics-based rupture models for FDHA and the current implementation in an IAEA-TECDOC, as well as we present couple of examples of fault displacement prediction of past earthquakes

GROUND MOTIONS PREDICTION FOR HAZARD ASSESSMENT IN THE VALLEY OF MEXICO ASSOCIATED WITH EARTHQUAKES IN THE TRANS-MEXICAN VOLCANIC BELT

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The Trans-Mexican Volcanic Belt (TMVB) is an active mountain chain being deformed by an extensional stress regime with numerous active faults. Although a few significant shallow earthquakes ($M>=6.5$) originated in the TMVB, the background seismicity is low. The available seismic hazard studies are mainly based in the instrumental seismicity catalog. One emblematic example of potentially risky events is the Acambay (Ms=6.9) normal-faulting earthquake in 1912, 100 km northwest from Mexico City. To improve the seismic hazard assessment for such rare events, we propose the simulation of several realistic scenario earthquakes in 3D, within the central part of Mexico by means of a hp-discontinuous Galerkin finite element method (DG-FEM) that handles both unstructured domain decomposition and different approximation orders per element in space (DGCrack, Tago et al., 2012). It solves the velocity-stress formulation of the visco-elastodynamic equations in 3D with rock quality factors, Qs and Qp, chosen to be nearly constant in the frequency range of interest. We present results of the tetrahedral meshing of the Central part of Mexico, incorporating the real topography, a 3D tomographic velocity model, a 2 km thick layer of low velocity associated to the TMVB, a 3D basin model for the Valley of Mexico (Cruz-Atienza et al., 2016) and both, planar and non-planar fault-system models of the Acambay-Tixmadejé graben. We build broadband kinematic rupture scenarios following Pulido et al. (2015) and Villafuerte et al. (2019). The simulations of the strong motions are generated in the reference hardrock station CU up to 1 Hz, then PGA, PGV and spectral responses throughout the Valley of Mexico are estimated using response spectral ratios (Rosenblueth and Arciniega, 1992; Reyes, 1999).

ANALYSIS OF SIMULATED AND RECORDED FAR-FIELD GROUND MOTIONS FOR THE SPE AND DAG UNDERGROUND CHEMICAL EXPLOSIONS

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We investigate the far-field ground motion from underground chemical explosions of Phase I and Phase II of the Source Physics Experiment (SPE), recorded at the Nevada National Security Site (NNSS). Previous studies of SPE far-field seismic data largely focused on shear motion at distances less than 2 km from the source. In our analysis we investigate wave propagation effects using seismic recordings from several linear arrays of broadband seismometers, including two arrays across the Yucca Flat basin, covering epicentral distances up to 25 km. To analyze wave propagation characteristics affected by the underground basin structure, we performed several simulations using 3D velocity models covering an area of 37 km x 22 km. All simulations are performed using isotropic point sources in the frequency range 0-5Hz. Simulated waveforms for SPE-5 are used to test the quality of the 3D geologic model, especially in southern Yucca Flat where recorded data are characterized by very long duration; a clear indicator of basin reverberations. Analysis of coda-envelope amplitude ratios from different explosions and stations of equal epicentral distance suggests significant path and site effects and a potential source depth dependence of coda wave amplitude. Comparisons of recorded and simulated waveforms using 1D and 3D models of shallow structure demonstrate that the 3D basin structure contributes to generation of shear motion observed at basin sites. The inclusion of 3D wave scattering, simulated by correlated small scale stochastic velocity perturbations in the 3D model, improves the fit between the simulated and recorded ground motions. Attenuation analysis using recorded and simulated coda envelopes informs future model iterations and isolates the scattering effects.

SENSITIVITY TESTS OF TOPOGRAPHIC EFFECTS ON 3D SIMULATED GROUND MOTIONS IN RENO, NEVADA

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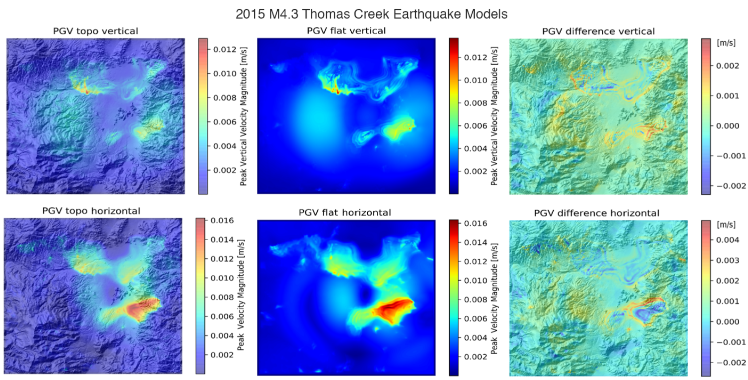
The availability of increased compute power has enabled the construction of 3d physics-based models that facilitate the exploration of the effects of geologic basins on the intensity and duration of shaking from earthquakes. As the resolution of these simulations improves, surface topography may have increasingly pronounced effects on modeled ground motions. We have constructed two material property models of the Reno-area basin in Northern Nevada. A framework using Python, pySW4, Dask, HDF5, and sklearn streamlines the construction of these material models, as binary "rfiles" at 35 m resolution. The rfiles are the geologic-model input to seismic computations with the SW4 code from Lawrence Livermore National Laboratory and the Computational Infrastructure for Geodynamics. Both models include basin geometry as estimated by gravimetry. One model includes the almost 2 km of topographic features that surround the urban area. The other is a flat-earth model having the same basin thicknesses. Previous work has explored flat-earth basin models by comparing 3.3 Hz synthetics generated with SW4 against recorded ground motion from the 2008 M4.9 Mogul earthquake. Many of the synthetic seismograms showed significant mismatches to recordings. We extend this analysis with sensitivity tests contrasting the flat-earth and the topographic models, and adding an examination of recordings of the 2015 M4.3 Thomas Creek earthquake. This current work examines the role of topography in improving the fit of the synthetics to the recordings. Increasing the maximum frequency of the synthetics from 2.2 Hz to 3.3 Hz increases the effects of topography. The topographic models show somewhat longer shaking durations, though still not approaching the recorded durations in and near the basin.



THE 2017 ULA (MUĞLA) EARTHQUAKE SEQUENCE

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In 2017,three moderate sized events took place near the town of Ula(Muğla) on eastern edge of Gokova Bay. Seismologically reported values in catalogs especially the depths of earthquakes do not generate sufficient deformation to explain geodetically observed motion but InSAR data shows that significant surface deformation. In order to better assess the location informations,we relocated all the aftershocks by using the DD. Source mechanisms of events are estimated by utilizing the generalized gCAP for regional body and surface waveform inversion.Fault mechanism solutions indicate that the events are associated with different striking normal faults at shallow depths.

Surface deformations of earthquakes were obtained from Sentinel-1A/B satellites. Inversion of geodetic data cannot be performed because of the atmospheric noise. We need additional analysis to minimize tropospheric noise. Results of seismological analysis were used as constrain for forward models (Beat Tool (Vasyura-Bathke et all, in press)) to stay in error margins. Modeling result of April 2017 activity indicates a S-dipping NE-SW trending fault at shallow depths and the second seismic sequence forward modelling indicates an almost EW trending, S-dipping normal fault geometry.

Results from seismology and geodesy both indicate that the 2017 activity occurred along a previously unknown normal fault instead of the southeastern branches of the nearby Muğla Fault as proposed earlier. The new fault structure, which was recently mapped by Akyuz et al.(2018) on the surface follows the trend of active faults in Gokova Bay to the east and could shed light on the active tectonics of the Gokova fault zone.

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DYNAMIC EARTHQUAKE RUPTURE MODELING IN FLUID-RICH FAULT NETWORKS CROSSING SPACE-TIME SCALES: FROM SUBDUCTION ZONES TO INDUCED SEISMICITY

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Modeling how faults slip requires generally numerical methods that span a large range of spatial and temporal scales. In subduction zones, in addition, pronounced geometric and rheological complexity needs to be accounted for. High-resolution 3D dynamic rupture earthquake scenarios can integrate complex megathrust-splay fault geometries, high resolution topography and bathymetry, 3D subsurface structure and off-fault deformation, as demonstrated in dynamic rupture earthquake scenarios of the 2004, Mw 9.1-9.3 Sumatra-Andaman earthquake and tsunami (Uphoff et al., SC'17). Physics-driven, mechanically viable interpretations can be integrated synergistically with established data-driven efforts which is specifically useful in regions lacking near-source observations. However, initialising such models with self-consistent fault and surface geometry, fault stress and rheology, fluid pressures and subsurface lithology is challenging. This can be overcome in coupled frameworks such as developed in the ASCETE project (www.ascete.de) connecting subduction dynamics over millions of years, seismic cycling and earthquake dynamics down to fractions of a second, as well as tsunami propagation and inundation. Earthquake dynamics in fluid-rich fault networks are also prevailing on the much smaller scales of geo-reservoirs. Fault networks at geo-reservoir scales are inherently geometrically complex; the dynamic stress released during the rupture process interacts with multiple adjacent fractures and 3D Earth structure acting as interdependent reinforcing and inhibiting factors for rupture cascading. Physics-based modeling can explore the richness of the dynamic response of such geo-reservoirs, specifically focusing on geometrical and structural complexity.

INSIGHTS INTO RUPTURE PHYSICS FROM INDUCED SEISMICITY

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Better understanding of the conditions controlling nucleation and size of earthquakes is of critical importance. Although injection-induced earthquakes pose a serious seismic hazard, they also offer an opportunity to gain insight into rupture physics.

Galis et al. (2015) derived fracture-mechanics-based relations between the area and overstress of overstressed asperity and the ability of ruptures to either stop spontaneously (arrested ruptures) or runaway (super-critical ruptures). These relations were verified via extensive 3D dynamic rupture simulations on faults governed by linear slip-weakening friction. Later, Galis et al. (2017), extended previous results and derived estimate of the size of arrested ruptures nucleated by localized stress perturbations. Fluid-injection induced earthquakes are triggered by pore-pressure concentrations that can be reasonably constrained using pore-pressure diffusion models and information about volume of injected fluids. Utilizing this fact, they developed a theoretical scaling relation between the largest magnitude of self-arrested earthquakes and the injected volume. They find it consistent with observed maximum magnitudes of injection-induced earthquakes over a broad range of injected volumes, suggesting that, although runaway ruptures are possible, most injection-induced events have been self-arrested ruptures. Recently, we investigated impact of elongated overstressed asperities on rupture nucleation and arrest and we found that the ruptures are dominantly controlled by area of asperity, even for elongated asperities.

EARTHQUAKE DYNAMIC RUPTURE MODELING CONSTRAINED BY SEISMIC OBSERVATIONS

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Dynamic rupture models take into account physical processes governing the fault rupture, and thus their use seems to be the proper way to model realistic near-source synthetic seismograms. However, there is no guarantee that they provide realistic earthquake ground motions. Indeed, an improperly chosen distribution of dynamic parameters may lead to over- or under-estimated ground motions with respect to observations. To address this issue, we present dynamic rupture modeling using spontaneously propagating and stopping ruptures governed by linear slip weakening friction law with spatially variable dynamic parameters. The models are designed within a Bayesian framework (using Markov Chain Monte Carlo approach) subject to one of the following constraints: i) waveforms observed for a specific earthquake, and ii) Ground Motion Prediction Equations (GMPEs). In the first case, we apply the dynamic inversion to the 2016 Mw 6.2 Amatrice, Central Italy, earthquake. We obtain ∼5,000 accepted model samples from a million of visited models. In agreement with previous kinematic inversions, the dynamic rupture initiated by a localized transient nucleation followed by bilateral rupture propagation. The rupture accelerates towards the heavily damaged city of Amatrice where the peak acceleration of 0.8 g was measured. In the second application, we use the framework to simulate earthquake ruptures compatible with GMPEs. As a result, we obtain a variety of M6-7 realistic events with relatively complex rupture propagation. We explore the inferred dynamic and kinematic source parameters including fracture energy, radiated energy and efficiency, stress drop and its variability. Our study demonstrates how to construct dynamic rupture models with realistic ground motion radiation.

EARTHQUAKE RUPTURE MODELING OF ROUGH FAULT IN ROCK LAB EXPERIMENTS

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Fault roughness is present at various scales. From limestone samples taken at fault outcrops, Candela et al. (2009) has characterized scaling properties of fault roughness covering 6 orders of magnitudes of fault-topography wavelengths (40 m to 40 m). The fault topography perturbs the local stress field and produces heterogeneities of slip and rapid acceleration and deceleration of the rupture front (Dunham et al., 2011). As a result, roughness enhances high seismic frequency radiation and more complexity on the rupture process. However, roughness not only affects ground motion and rupture propagation but It also has an impact on the nucleation process. In fact, recent rupture modeling on rough faults makes use of rate and state friction with aging (tal et al., 2018) and slip law (Ozawa et al., 2019) to investigate the effect of fault roughness on the nucleation process. This work follows these approaches and perform earthquake cycle and rupture modeling for rough faults obtained from rock lab experiments of Selvadurai et al. (2015, 2016). To include fault roughness measured in the lab, we make use of the H-matrix methods and rate and state friction to mimic the rupture and nucleation process recorded during rock lab experiments.

EQUATION OF MOTION FOR DYNAMIC RUPTURE PULSES

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Seismological observations tend to indicate that major earthquake ruptures propagate along seismogenic faults pulse-like [Heaton PEPI 1990], such that any given point of the ruptured fault accumulates slip over duration much shorter than the overall fault rupture time. Numerical simulations of elastodynamic rupture on strongly dynamically weakening faults [Gabriel et al JGR 2012, Noda et al JGR 2009] have shown that slip pulses do arise spontaneously, but generally are inherently transient even on uniformly-stressed, homogeneous faults - either arresting or accelerating to the limiting speed, prompting transition to crack-like and/or supershear mode.

In this work, we have developed an equation of motion (EoM) for transient pulse motion based on the analysis of the fault field perturbation around a steadily propagating pulse solution. The latter can be readily obtained and fully parametrically characterized for a given fault rheology (see, e.g., Garagash [JGR 2012] for steady pulses driven by thermal pressurization). We validate the pulse EoM by full elastodynamics rupture simulations in the case of a fault dynamically weakened by thermal pressurization (TP).

The rate of pulse slip in the EoM is proportional to the difference between the actual background shear stress resolved on the fault plane and the “steady-state pulse value” of the background stress corresponding to the instantaneous value of pulse slip. This allows for a simple prediction that steadily propagating pulses are unstable when the corresponding pulse slip is a decreasing function of the background stress. This is the case for TP pulses (rendering them unstable), and, likely more generally, for fault rheologies characterized by strong weakening with accrued slip and/or slip rate.

EoM also quantifies how a transient pulse responds to heterogeneity in fault stress and strength (step up/down in stress leads to pulse deceleration/acceleration) allowing, for example, for a sustained, nearly-steady propagation on rough-stress faults.

CAN BROAD-BAND EARTHQUAKE SITE RESPONSES BE PREDICTED BY THE AMBIENT NOISE SPECTRAL RATIOS? INSIGHT FROM NUMERICAL EXPERIMENTS

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Perron et al. (2018) reported that standard spectral ratios computed from seismic noise measurements (SSRn) or from earthquake recordings (SSRe) could be very similar for couples of stations sharing similar site conditions. They propose that such similarity can be exploited efficiently, in the so-called hybrid SSR approach, to extrapolate spatially the amplification function measured from earthquakes at a single site. In order to better understand the discrepancies, or similarities between SSRn and SSRe, we simulate numerically the 3D response of a canonical basin (having elliptical shape and $1D$ structure with depth) to noise and earthquake sources for frequencies up to 10 times that of the fundamental resonance of the basin. We compare the SSR produced by different sets of noise sources and evidence the shadow effect, hypothesized by Perron et al. (2018) to explain the discrepancies between SSRn and SSRe when the reference is chosen outside of the basin. We further evaluate the hybrid SSR approach for several stations located in the basin at different distances from the edges.

WAVEFIELD SIMULATION NEAR MENDOCINO TRIPLE JUNCTION FROM LOCAL EARTHQUAKES

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Waveforms from subduction zone earthquakes recorded by local stations are natural examples of wave propagation through lateral heterogeneous media. These waveforms carry fruitful information about subduction zone structure. We take advantage of a dense onshore and offshore array near the Mendocino Triple Junction and the abundant seismicity there to study the material properties of the interface of the subducted Gorda plate by comparing forward modeling results with direct observations.

In this study, we focus on two types of phases: multiple converted phases generated by the interaction between direct P or S wave with slab interface and related impedance contrasts as well as “trapped” waves generated by earthquakes happened near the slab interface.

Multiple Ps and Sp phases converted from slab interface are observed between direct P and S waves on the waveform sections. The shape of the converted phases show azimuth and frequency dependences. SPECFEM2D/3D are used to generate synthetic waveforms and to estimate the impedance contrast across the slab interface as well as focal mechanism effects on the converted phase waveforms.

Subduction slab interfaces are usually imaged as a low velocity zone from receiver function or active source seismic studies. This low velocity zone plays an important role in interseismic coupling and earthquake ruptures. The S wave waveforms from the near interface events have much longer durations than earthquakes below or above the slab interface in the same area and have a characteristic frequency. Forward modeling results are used to infer the thickness, velocity reduction and Q value of this low velocity layer.

FDTD MODELLING OF SEISMIC WAVE PROPAGATION IN POROUS MEDIA

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We have developed a discrete representation of a strong material heterogeneity in the poroelastic medium and poroviscoelastic medium in the low-frequency regime. The representation makes it possible to model an arbitrary shape and position of an interface with sub-cell resolution in a uniform spatial grid. The computational efficiency of the finite-difference grid is unchanged compared to the scheme for a homogeneous and smoothly heterogeneous medium because the number of operations for updating stress-tensor, fluid pressure and particle velocities is the same. The only difference is that it is necessary to evaluate averaged grid material parameters once before the finite-difference simulation itself. The developed representation extends the possibilities of the finite-difference modelling of seismic wave propagation in the poroelastic medium.

We numerically demonstrate accuracy and sub-cell resolution of our modelling on a variety of canonical models by comparing the finite-difference solutions with analytical solutions and also an independent numerical method. We also present preliminary results of investigating effects of presence of a porous water-saturated sediment layer (described by a depth of a water table, porosity and permeability) in local surface sedimentary basins on a set of earthquake ground motion characteristics.

OBSERVATIONS AND SIMULATIONS OF LARGE EARTHQUAKES ON CREEPING FAULTS

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Locked faults release their tectonic strain during earthquakes and postseismic slip. In contrast, creeping faults release a sometimes significant portion of their tectonic strain aseismically, over long periods of time. Creeping faults are uncommon in continental active-tectonic regions, but more than 20 have been detected in countries around the world. The most famous is a 100-km-long portion of the San Andreas fault, in central California.

A few of the world's continental creeping faults have been observed to produce large earthquakes, and the question is if these large earthquakes behave similarly to or differently from large earthquakes on locked faults.

Harris and Abrahamson [2014] showed the peak strong ground shaking from well-recorded locked-fault earthquakes and creeping-fault earthquakes of the same magnitude to be similar.

A review article by Harris [2017] investigated if large earthquakes on creeping faults and large earthquakes on locked faults produce similar or different rupture areas. The finding was that the rupture areas are similar for earthquakes of the same magnitude.

A caveat for both studies is that the largest creeping-fault earthquakes were magnitude 6.6, and larger earthquakes on creeping faults might behave differently.

When there is a paucity of observations, scientists can use computational simulations to provide results. The Hayward fault in the San Francisco Bay Area is an active creeping fault that produced a large earthquake in 1868. It would be good to know what the next large Hayward fault earthquakes will look like. Simulations are used to investigate what might control a dynamically propagating earthquake rupture that starts on the Hayward fault or its companion faults to the north and south.

ANALYTICAL SOLUTION OF DYNAMIC SELF-SIMILAR CRACK GROWTH UNDER DISTANCE-WEAKENING FRICTION

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The relationship between the evolution of slip and weakening of friction is significant for earthquake dynamics and has been estimated by theoretical, experimental, and observational studies. Because dynamic rupture growth during an earthquake seems to be self-similar and slower than the theoretical limit (i.e., Shear or Rayleigh wave) velocity, the fracture energy and the slip-weakening distance, D_c, should be scaled by the current ruptured length. In case of a steady-state pulse-like rupture model, Rice et al. [2005 BSSA] obtained a theoretical approximation of the fracture energy as a function of given stress parameters under a distance-weakening friction model, which mimics a slip-weakening model. Their pulse-like model contributed to the quantification of fracture energy for many pulse-like earthquake ruptures. However, also a self-similar model may be helpful for the quantification in cases of crack-like rupture modes.

In this study, we obtain an analytical solution of a mode-III self-similar dynamic crack model under self-similar distance-weakening friction. The weakening distance can be determined so that slip-rate and stress are finite at the crack tip. As a result of this calculation, we can obtain the dependence of D_c on the rupture velocity and given stress parameters. Actually, D_c and rupture velocity could be estimated on the basis of observational data, while stress parameters are not. Hence, this relationship may contribute to the estimation of fracture energy or stress parameters along very long dip-slip faults, on which mode-III rupture propagation dominates.

HOW CAN DYNAMIC RUPTURE MODELERS PRODUCE USEFUL INSIGHTS FOR SEISMIC HAZARD ASSESSMENT PRACTITIONERS?

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For years the ground motion prediction (GMM) in seismic hazard (SHA) has been based on ground motion (GM) records, limited at large Mw and in near-field. In practice, close to faults, SHA relies on extrapolations of seismic sources (magnitudes and rupture scenarios) and GM. Thus, significant uncertainties (GM variability) remain in the GMM. These motivate the need for physics-based (PB) SHA. We face several challenges and strategies related to different aspects of rupture dynamics and seismic wave propagation. 2 common needs are clear: validation against data and an evaluation of uncertainties on results. While the first should be achieved naturally, the second may change our habits as a community. I will discuss several of them pointing out critical points. First, in terms of seismic sources, EQs cycle and multi-fault rupture physics could be used to constrain the Mw (frequency and max) relevant to the SHA. Second, in terms of GMM, numerical simulations need validation against data before used for prediction. I will discuss paradox and challenges behind this (involving more than rupture physics). We should tackle 2 milestones routinely in our source inversions and rupture dynamics models of past EQs. 1) Identifying parameters controlling the GM (rupture velocity variations and directivity, distances from faults and asperities, rupture details, stress variations). 2) For blind prediction, generic parametric set up and scaling laws for dynamics need to be defined (absolute stress conditions, scaling for mean parameter values, and their variability). Finally, it is crucial to constrain uncertainties if we want our results used in SHA. For this we must change our current practice to document the negative results in the same way we do with positive results.

TOWARDS GROUND MOTION PREDICTIONS FOR A LARGE HIKURANGI SUBDUCTION EARTHQUAKE: LESSONS FROM THE KAIKŌURA EARTHQUAKE

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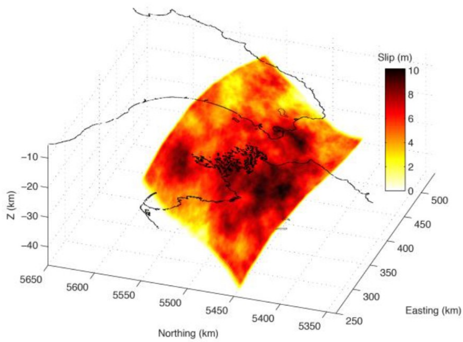
The 2016 M7.8 Kaikōura, New Zealand, earthquake struck the East coast of the northern South Island on November 13th 11:02 (UTM). The damaging earthquake generated extreme surface displacements, land deformations and ground motions, a regional tsunami and triggered significant slow slip events on the Hikurangi interface (Kaneko et al., 2017). Sadly, it also caused 2 fatalities and many New Zealanders were affected by this earthquake. The overall earthquake rupture process as suggested by advanced source models (Hamling et al.,2017; Holden et al.,2017; Kaiser et al.,2017; Bradley et al.,2017) is complex and unexpected. The earthquake bypassed the Hope fault, largest source of regional seismic hazard, as it ruptured exclusively to the North (despite most of the stress accumulated from the 2010-2016 Canterbury earthquake sequence was to the South). Source models based on teleseismic and/or regional data suggest that the interface did contribute to the overall rupture (Bai et al.,2017; Duputel & Rivera,2017; Kaiser et al.,2017). However, many observations strongly support evidence of minor (if any) contribution of the interface in the overall rupture (Holden et al.,2017; Clark et al.,2017; Cesca et al.,2017). These unexpected source characteristics are not considered into best practice but significantly impact ground motion results. We entertain a range of realistic source characteristics (Kaneko et al., 2018) of a future Hikurangi earthquake to explore ground motion variability. Our findings show that strong ground motion is mostly controlled by rupture directivity, stress drop, asperity size, and the presence of sediments and exhibits a large variability despite the tight range of “realistic” parameters employed in our simulations (Holden et al.,2018).



PHYSICS OF INJECTION-INDUCED EARTHQUAKES UNVEILED BY SEISMIC WAVE ANALYSIS AND NUMERICAL MODELS

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Injection-induced seismicity is considered to be primarily caused by the fault pore pressure change and the poroelastic deformation of the reservoir. Using spectral ratio approaches based on empirical Green's functions, we [Huang, Ellsworth, and Beroza, 2017] have shown that stress drops of induced earthquakes are indistinguishable from those of tectonic earthquakes in the central US, indicating that most stress released by induced seismicity released has been accumulated by tectonic activities and the fluid-induced fault stress change is relatively small compared to the absolute fault stress levels. By forward-modeling the rupture directivity of major induced earthquakes assuming the Haskell model, we find that the 2016 Fairview earthquake that occurred near a high-pressure injection zone ruptured toward injection wells, whereas the 2011 Prague and 2016 Cushing earthquakes ruptured away [Lui and Huang, 2019]. Such observations are consistent with numerical simulations with energy-based crack propagation and fluid flow, which show that high-pressure injection and low-stress faults can together favor ruptures propagating back to injection wells, whereas rupture tends to propagate away if injection pressure is low [Dempsey and Suckale, 2016]. We also conduct fully dynamic earthquake cycle simulations to investigate the effects of fluid-induced stress perturbations on the timing of size of induced earthquakes. Our key finding is that while fluid injection is generally believed to trigger the next event to occur sooner, small fluid-induced stress perturbations can also trigger substantial aseismic slip that delays subsequent earthquakes and lengthens the seismic cycle.

THE EFFECT OF SCATTERING AND INTRINSIC ABSORPTION ON SITE- AND REGIONAL-KAPPA

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The amplitude of seismic waves drops as these propagate from the source to the site of observation because of geometrical spreading, absorption, and scattering. Earthquake recordings at the surface usually exhibit a lack of high-frequency energy compared to theoretical source radiation models. The ability to predict the amount of energy that will reach a target location from an earthquake source represents a critical issue in ground motion prediction seismic and hazard studies. The high-frequency fall-off observed in acceleration spectra of ground motions is typically expressed in terms of the empirical frequency parameter kappa (Anderson and Hough, 1984), having both site and regional contributions. Altough kappa has a large impact in seismic hazard studies its physical origin is not yet fully understood. In this study we investigate the relative contribution of scattering and intrinsic attenuation by means of numerical simulations. We adopt a Monte Carlo technique to solve the radiative transfer equation in three-dimensional media characterized by laterally variable background velocity (e.g. basins) and/or variable scattering and intrinsic attenuation parameters. Multiple sets of synthetics seismograms spanning a broad frequency range (0-20Hz) are computed at hundreds of randomly distributed receivers between 20km and 100km from the source. We estimate kappa following the procedure of Anderson and Hough (1984) based on the linear regression of the synthetic log Fourier Amplitude Spectrum (FAS) between 2 Hz and 15Hz. Our analysis provides quantitative estimates of the contributions of the scattering and absorption mechanisms on the apparent attenuation measured from the Fourier spectra of ground motion recordings.

A SOURCE SPECTRUM WITH A DOUBLE-CORNER FREQUENCY AND ITS PHYSICAL IMPLICATIONS FOR THE EARTHQUAKE SOURCE

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We introduce a self-similar, double-corner-frequency (DCF) source spectrum, which in conjunction with a stochastic ground-motion model, can reasonably reproduce the peak ground acceleration (PGA) and peak ground velocity (PGV) of the NGA West-2 data set for magnitudes 3.3 to 7.7. Its displacement spectrum amplitude is constant for frequencies less than f_{c1}, decays as f^{-1} between f_{c1} and f_{c2}, and f^{-2} for frequencies larger than f_{c2}. The two corner frequencies f_{c1} and f_{c2} scale with magnitude (M) as: (1) $\log(f_{c1}(M)) = 1.754 - 0.5M$ and (2) $\log(f_{c2}(M)) = 3.250 - 0.5M$. The apparent single corner frequency (f_c^A) of the classic ω^{-2} model, defined as $f_c^A = \sqrt{f_{c1} f_{c2}}$, satisfies (3) $\log(f_c^A(M)) = 2.502 - 0.5M$. We find that relation (1) is consistent with the known self-similar scaling relations of the rupture duration (τ_d), if τ_d relates with f_{c1} as $\tau_d = 1/((\pi f_{c1}))$. The relation (3) is tightly associated with the constant "stress parameter", previously noticed in strong motion community. We find that simultaneously satisfying long- and short-period seismic observations requires $f_c^A \approx 1.78/\tau_d$, rather than $((0.6\ or\ 1.0))/\tau_d$ used in prior analyses. The DCF predicted radiated energy and apparent stress agree with global estimates of these parameters. Such an empirical model explains why the average stress drop from seismological studies is different from the stress parameter used to estimate PGA and PGV. The physical explanation of the high corner frequency f_{c2}, which is a consequence of relations (1) and (3), is not clear yet. Its inferred characteristic time is much smaller than rupture duration of asperities; f_{c2} may be related with the average rise time $\overline{T}_r = 0.8/f_{c2}$ on the fault inferred from the slip models; or f_{c2} might be associated with the average peak time of the fault slip on asperities.

ACCELERATING FORESHOCKS OF CRUSTAL EARTHQUAKES CONTROLLED BY FRICTIONAL HETEROGENEITIES

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While most earthquakes start abruptly, with no evidence for a nucleation process, accelerating foreshocks within or in the vicinity of the eventual mainshock rupture zone for some moderate to large crustal earthquakes have been documented recently. For example, Tape et al. (2018) reported nucleation signals of crustal earthquakes in the Minto Flats fault zone in central Alaska, manifested by ∼20 seconds of simultaneous high-frequency foreshocks and a very low-frequency earthquake. One potential explanation for such observations is a slow slip front propagating over the fault and triggering foreshocks as it transitions into the mainshock rupture (e.g., Tape et al., 2018). Another explanation may be that accelerating foreshocks represent cascading sequences of fault ruptures due to static and/or dynamic stress changes, without underlying slow slip (e.g., Ellsworth and Bulut, 2018). Here we show that a numerical fault model incorporating full inertial dynamics and rate-and-state friction laws with frictional heterogeneities can reproduce the accelerating foreshocks observed in the Minto Flats fault zone in central Alaska. Our results suggest that a slow physical process, such as slow slip or fluid diffusion, in between small-scale, velocity-weakening asperities is needed to generate accelerating foreshocks. Our results further suggest that the time scale of accelerating foreshock sequences depends on the degree and size of frictional heterogeneities and tectonic loading rates. The model may also explain why the occurrence of accelerating foreshocks is relatively uncommon.

ULTRA-LONG DURATION OF SEISMIC GROUND MOTION ARISING FROM A THICK, LOW VELOCITY SEDIMENTARY WEDGE

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Sedimentary basins are known to amplify and increase the duration of ground motions that accompany earthquakes. A similar phenomenon is expected but not as well documented in low seismic-velocity accretionary prisms along subduction margins. In this study, we report anomalously long duration of long-period ground motions observed in the North Island of New Zealand during seismic wave propagation from the M7.8 Kaikoura earthquake 600 km away. Unique waveform data captured by strong-motion, high-rate GPS, and ocean bottom pressure sensors reveal that long-period ground motions lasted longer than 450 seconds in the northeastern North Island. These waveforms indicate one of the longest durations of long-period (10 seconds and longer) ground motions ever recorded at similar epicentral distances for comparable, large earthquakes. To understand the underlying mechanism, we use numerical simulations of seismic wave propagation. We find that a velocity model that includes an accretionary prism, modeled as a large-scale (approximately 30,000 km x km) wedge characterized by extremely low seismic wavespeeds, can explain the observed long durations of long-period ground motions, as the reverberations of seismic waves within the low-velocity wedge. We show that the long duration of long-period ground motions leads to prolonged dynamic stressing on the plate interface, likely accentuating the triggering of slow slip that occurred following the Kaikoura earthquake. Accretionary prisms characterized by extremely low seismic velocities may enhance the generation of tsunami earthquakes and dynamic triggering of slow slip events observed in the northern Hikurangi and other subduction margins.

DYNAMIC RUPTURE SIMULATIONS OF A VERTICAL STRIKE-SLIP FAULT OF M6.5 CLASS CONSIDERING SPATIALLY-HETEROGENEOUS STRESS-DROP DISTRIBUTIONS

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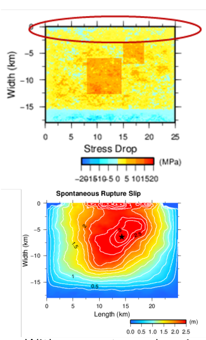
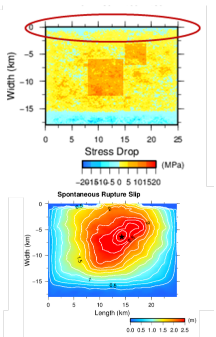
We investigated here the effects of source parameters that describe the complex nature of the source rupture process, with special focus on the spatial heterogeneity of the stress drop on the fault. We considered here both random fluctuation (Pitarke et al. 2009) and two rectangular asperities where the average stress drop is twice (6.4 MPa) as large as the global one (3.2MPa). The area of asperities is followed by the scaling low (Irikura & Miyake 2002).

We also consider the depth dependence of the stress drop distribution outside of the major seismogenic zone. Geometric parameters such as the rupture initiation point, relative separation distance between two asperities, and the depths of the two asperities are chosen to investigate. The assumed fault is a vertical strike-slip fault with the size (L x W)=(25 km x 18 km). The dynamic rupture simulation was performed by the FDM code using a slit-node formulation (Dalguer & Day 2007).

First we confirmed if the averaged slip and the peak ground velocity correspond to the value for the empirical relationship or not. Then we investigated the effects of Dc, asperity depths, and the stress drop distribution along the depth on the final slip distribution and the resultant peak ground velocity distribution. If we put asperities in the deeper part of the fault, we could not see much of the surface rupture, while if we put two shallow asperities the resultant surface break (displacement) becomes larger. If we decrease the stress drop near the surface, such a large surface break would be no longer emerged on the surface. The figure on the left shows the normal case, while the one on the right shows the small stress drop case. We can see apparent dependence of the shallow stress drop setting on the slip near the surface.



With some stress drop in the shallow part



Without stress drop in the shallow part

CURVED FAULT STRIATIONS PRESERVE THE DIRECTION OF DYNAMIC RUPTURE PROPAGATION

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Slip-parallel grooves (striations) on fault surfaces are considered a robust indicator of fault slip direction, yet their potential for recording details of earthquake rupture dynamics has received little attention. During the 2016 Kaikōura earthquake, 10-plus meters of dextral strike-slip on the steeply-dipping Kekerengu fault exhumed $>$200 m^2 of fresh fault exposure (free faces) where it crossed deep gullies in bedrock. Inscribed upon these surfaces, we observed individual striae up to 2 m long, all of which had formed during the Kaikōura earthquake. These were typically curved. Collectively, the striae recorded a rotation of the co-seismic slip vector that was common between sites. Using simulations of spontaneous dynamic rupture on a vertical strike-slip fault we reproduce the observed, curved morphology of striae on the Kekerengu fault. Our models assuming strike-slip pre-stress reveal that vertical tractions are induced co-seismically by fault slip in the so-called cohesive zone. These result in some local dip slip and temporal changes in slip direction. We show that the sense of striae curvature is sensitive to the direction of rupture propagation. To match the geometry of Kekerengu fault striae, our simulations require the rupture propagating from south-west to north-east, which agrees with the known rupture direction of the Kaikōura earthquake. Our study highlights the potential for fault striae to record aspects of earthquake rupture dynamics, including the rupture propagation direction of paleo strike-slip earthquakes.

INSIGHTS INTO SOURCE PARAMETERS OF SEISMICITY CAUSED BY HYDRAULIC FRACTURING AT THE HORN-RIVER BASIN, BRITISH COLUMBIA

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In recent years there has been increasing public concern regarding ground motions caused by induced seismicity (Ellsworth, 2013). These earthquakes have led to abandonment of projects, investment losses and litigation issues regarding compensation for damage (Ellsworth, 2013). It is still debated as to whether induced seismicity is caused by significantly different rupture physics compared to natural seismicity. This is critical in forming accurate Ground Motion Prediction Equations (GMPE's) for hazard assessments. This study investigates stress drops and key source parameters from seismicity caused by hydraulic fracturing of tight shale at the Horn-River basin, British Columbia. We calculate stress drops for 100 events (-0.9 $<$Mw $<$0.5) using 1100 high quality SV phase-arrivals. Our preliminary results suggests an average stress drop of 0.3 MPa which is below the global average of 4 MPa (Allmann and Shearer, 2009). This could suggest distinctly different physics for induced seismicity. However, it is likely that attenuation is playing a key role which could result in apparent corner frequencies.

DYNAMIC SOURCE INVERSION FOR PHYSICAL PARAMETERS CONTROLLING THE MW 6.3 2017 LESVOS EARTHQUAKE

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We perform a Bayesian dynamic finite-extent source inversion to constrain the physical parameters and stress conditions that governed the Mw 6.3 2017 Lesvos earthquake. The mainshock occurred on 12 June, offshore the south-eastern coast of the Greek island of Lesvos in the north Aegean Sea. It caused 1 fatality, 10 injuries and extensive damage to the southeastern part of the island. The earthquake likely ruptured the eastern segment of the Lesvos Basin fault dipping to the south-west at 43^{circ} with normal faulting mechanism (Kiratzi, 2018). We start with centroid moment tensor inversion, obtaining the south-west dipping nodal plane compatible with the hypocentre location. Considering this plane as the fault plane, we perform the dynamic finite extent source inversion based on an elliptical model of rupture (Twardzik & Madariaga, 2014). The forward problem (dynamic rupture simulation) is solved by a 3D finite difference method assuming linear slip-weakening friction law on a planar fault (Madariaga et al., 1998). Coupling the obtained rupture evolution with Green's functions precalculated by the discrete wavenumber method (AXITRA) allows us to evaluate the misfit between synthetic and observed waveforms at 19 stations with fault distances of up to 100 km. The inverse problem is solved using the Parallel Tempering Monte Carlo algorithm (Sambridge, 2013), which samples the posterior probability density function of model parameters that determine frictional and stress conditions on the fault. This way we obtain not only the model that provides the best fit with the observed seismograms, but we also examine the uncertainty, stability and correlations of the inverted dynamic and kinematic source parameters.

A UNIFORM-GRID FINITE-DIFFERENCE MODELLING OF SEISMIC WAVEFIELDS AROUND A VACUUM CAVITY

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A uniform-grid finite-difference (FD) modelling of seismic wavefields around a vacuum cavity still poses a non-trivial problem because the traction-free condition has to be satisfied at a curved interface between the vacuum and elastic/viscoelastic solid. We present an algorithm that we have developed using the immersed-interface approach.

We use a staggered-grid FD scheme, 4th-order accurate in space and 2nd-order accurate in time, SGFD (4,2), at all grid points except those at or near the boundary of the cavity. At those points we apply SGFD (2,2). A near-grid point means that for updating wavefield at this point, the FD stencil needs at least one grid point inside cavity. We calculate the wavefield at the grid points inside cavity using an immersed-interface method in order to account for the vacuum-solid boundary conditions. That is, we apply a special extrapolation inside a 9x9x9 grid-point cube centred at the near point. Calculation of the 9x9x9 coefficients can be performed just once – when preparing a grid model. Effectively, the FD simulation itself is then only about 10% slower compared to the case of the same model without cavity. For calculating the coefficients we use subroutines generated by the Mathematica software. The key for using Mathematica is an appropriate parameterization of the interface.

We verified our FD algorithm by comparing the FD simulations with the finite-element simulations. We have not encountered any problem with accuracy or instability even for long time windows (we tested windows up to 25 000 time levels). The level of agreement is excellent.

We have applied the developed FD algorithm for simulating seismic wavefields in the medium modified by an underground nuclear explosion.

ENERGY BUDGET OF EARTHQUAKES: CONNECTING REMOTE OBSERVATIONS WITH LOCAL PHYSICAL BEHAVIOR

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Many seismological studies seek to shed light on earthquake rupture physics using averaged event quantities, such as the average slip and static stress drop, as well as energetic estimates such as the radiated energy, (averaged) breakdown energy, and radiation efficiency. These inferences rely on the use of idealized rupture models, whereas the actual spatial distribution of slip and local stress change may vary substantially throughout the ruptured area. The relationship between observationally-inferred average rupture characteristics, such as breakdown energy and radiation efficiency, and their actual values is therefore not directly evident. We explore this relationship using fully dynamic simulations of sequences of seismic and aseismic slip incorporating standard rate-and-state friction as well as enhanced dynamic weakening due to thermal pressurization (TP) and flash heating.

We find that standard energy considerations inspired by dynamic fracture mechanics generally hold for simulations that produce crack-like shear ruptures, within a relatively modest error of a factor of 2. Moreover, models incorporating TP are able to reproduce the observationally inferred trends of increasing breakdown energy with event size, magnitude-invariant stress drops, and radiation efficiency around 0.5. In contrast, the standard energy budget does not apply to simulations that result in self-healing pulse-like ruptures, which are characterized by a substantial stress undershoot, and thus greater discrepancies between the average dynamic and static stress changes. If large earthquake ruptures propagate as such self-healing pulses, as have been suggested by a number of studies, then inferences about their energy budget need to be reconsidered.

INVESTIGATING THE BACK-PROJECTION METHOD USING SYNTHETIC RUPTURE MODELS: FAULT HETEROGENEITY, ARRAY DISTRIBUTIONS AND FREQUENCY DEPENDENCE

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The back-projection (BP) method has been widely used to image the rupture process of many large and moderate earthquakes since its first application to the 2004 Mw 9.2 Sumatra earthquake. However, some critical questions – relevant to the interpretation of BP results – remain unanswered. Some of the important ones are – why different arrays often capture different rupture features for the same earthquake? What physical properties of the fault can we infer from the BP results? Here we use kinematic earthquake rupture models, in which we exactly know the spatiotemporal evolution of the rupture process. Those models are set up with various rupture velocities, slip rates, fault orientations, and unilateral or bilateral ruptures. We compare BP results generated from a range of synthetic arrays with the prescribed rupture models. Results suggest the BP can only track heterogeneous ruptures. In a certain frequency band, the BP is sensitive to rupture heterogeneity in a limited size range, which explains the frequency dependent ruptures usually observed in subduction zones. When ruptures propagate in multiple directions simultaneously, the frequency of source energy recorded in the arrays are changed due to the Doppler effect of rupture directivity. The BP tends to track the rupture in a direction that produces dominant seismic energy in the array within a certain frequency bands used. In a next step, dynamic rupture models will be set up to examine the direct relation between BP results and earthquake dynamics. Understanding the physical implications of BP characteristics helps integrating modern observational techniques into dynamic rupture modeling, specifically with respect to the size and distribution of heterogeneities across faults.

INITIATION OF THE 2014 MW7.3 PAPANOA, MEXICO EARTHQUAKE INDUCED BY A PROCEEDING SLOW SLIP

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Slow slip events (SSEs) accommodate a fraction of the long-term geological loading at the depth of the the brittle-ductile transition, separating inter-seismically locked from continuous creeping parts of the megathrust. Recent geodetic analysis reveals that a slow slip event occurred just before the mainshock of the 2014 Mw7.3 Papanoa, Mexico earthquake [Radiguet et al., 2016]. This preceding SSE is thought to have caused substantially enough Coulomb stress changes in the hypocentral region to eventually trigger the mainshock. However, geodetic inversions lack resolution at depth and may only provide limited information on the dynamic stress evolution leading from slow slip to spontaneous dynamic earthquake rupture.

Here, we couple a quasi-dynamic slow slip cycle model with dynamic rupture and seismic wave propagation simulations to investigate potential triggering mechanisms linking the preceding SSEs and megathrust earthquakes exemplary for the Papanoa earthquake. The quasi-dynamic slow slip model utilises the Boundary Element Method (BEM) in the framework of laboratory-derived rate-and-state friction [Li and Liu, 2016; 2017] and is specifically suitable for complex 3D fault geometries. SSEs spontaneously appear at 40 km depth close to a pronounced fault kink of the subducting Cocos plate. A maximum slip of $\sim$25 cm is accumulated in between 20 and 43 km depth across the subduction interface. We export the transient shear stress perturbations generated by the deep SSEs as initial conditions for dynamic earthquake rupture simulations using the openly available software SeisSol (www.seissol.org). Based on the coupled approach, we will discuss if megathrust dynamic rupture can be constrained by fault stress perturbations generated by models of preceding SSEs.

DYNAMIC RUPTURE MODELING ON THE HAYWARD FAULT, NORTHERN CALIFORNIA– ESTIMATING COSEISMIC AND POSTSEISMIC HAZARDS OF PARTIALLY CREEPING FAULTS

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The hazards associated with partially creeping faults are not fully understood. In particular, the degree to which earthquake rupture is able to propagate into creeping areas of the fault, and the amount of shallow accelerated creep that would follow an earthquake are both uncertain. Both of these questions are gaps in our understanding of the physics of fault slip in general, but they are brought to particular societal relevance by the Hayward Fault, a partially-creeping fault which underlies the densely populated eastern San Francisco Bay Area, and has been identified as one of the two highest-hazard faults in California. In this study, we explore the likely controls that frictional conditions, fault geometry, and accumulated elastic stresses will have on probable rupture lengths, and on the ability of rupture to propagate into sections of the fault that creep interseismically. We use dynamic rupture modeling incorporating rate-state friction, which allows for mode switching between aseismic and coseismic deformation, to calculate scenario ruptures. We find that frictional heterogeneity alone can strongly limit the extent of rupture, and that the associated decrease in shear stress that comes from interseismic creep further confines rupture to locked patches. We then integrate these with static boundary element models, which allows for a physics-based assessment of interseismic stress evolution, to develop our pre-stress conditions and to account for rapid postseismic creep. While our study focuses on the Hayward Fault, our methods and findings will also enable more accurate scenario modeling and hazard analysis for earthquakes on other partially creeping faults.

MODELING EARTHQUAKE DYNAMIC RUPTURE WITH HYBRID FINITE ELEMENT - SPECTRAL BOUNDARY INTEGRAL APPROACH

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Earthquakes are among the costliest natural hazards on earth. The dynamical instabilities responsible for these events are linked to fundamental physics of fluid filled granular materials and rocks in the subsurface subjected to extreme geophysical conditions and coupled with long range static and dynamic stress transfer. Advances in computational earthquake dynamics are opening new opportunities in addressing the conundrum of scales in this extreme mechanics and societally relevant problem. Here, we will present a hybrid method that combines Finite element method (FEM) and Spectral boundary integral (SBI) equation through the consistent exchange of displacement and traction boundary conditions, thereby benefiting from the flexibility of FEM in handling problems with nonlinearities or small-scale heterogeneities and from the superior performance and accuracy of SBI. We validate the hybrid method using a benchmark problem from SCEC dynamic rupture simulation validation exercises and show that the method enables exact near field truncation of the elastodynamic solution. We demonstrate the capability and computational efficiency of the hybrid scheme for resolving off-fault complexities using an unique model of a fault zone with explicit representation of small scale secondary faults and branches enabling new insights into earthquake rupture dynamics that may not be realizable in homogenized plasticity or damage models. We are also planning to show preliminary results for earthquake cycle simulation using the hybrid scheme across both the dynamic and quasidynamic limits incorporating different examples of material and geometrical complexities.

TOWARDS MULTI-SCALE FAULT SLIP MODELING

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We present our latest work towards multi-scale fault slip modeling. (1) A ”cross-link” constraint method is introduced for numerically modeling dynamic slip on intersecting faults, without prescribing slip (dis-)continuation directions. The fault intersections are constrained by cross-linked split nodes, such that the slip can only be continuous on one of the two-way intersecting faults at a time and space. The method resolves the episodic intersection offset by examining the dynamic fault traction resulting from two sets of constraint equations, one for each slip direction. To verify this method, we modify the SCEC benchmark problems, number 14 and 15, by allowing the branch fault to step across the main fault. (2) A fundamental solution based finite element method is introduced to homogenize heterogeneous elastic medium under static and dynamic loading. This method incorporates Eshelby's strain perturbation in finite element weak forms. The resulting numerical model implicitly considers the existence of inhomogeneity bodies within each element. To demonstrate this method, we modify a dynamic fault slip problem, SCEC 205, by introducing a fault zone that contains different microstructures than the host matrix. We illustrate the fault zone effect in terms of seismic waveforms, slip contours and frequency contents. These two methods come with an open source finite element code ”Defmod-hybrid” which allows one to build a fault model that spans multiple aseismic and seismic cycles.

INSIGHTS INTO EARTHQUAKE PHYSICS REVEALED BY SLOWNESS-ENHANCED BACK-PROJECTIONS

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An improved understanding of the earthquake physics relies on better knowledge of earthquake rupture processes (earthquake nucleation, its complex rupture propagation, and the final arrest). Currently, the greatest challenge in this field is that the observations are behind the modeling efforts, making testing and validations of the ever-increasing rupture models impossible. In this talk, I present our effort of improving the resolution and reducing the uncertainty of back-projection imaging which allows us to address the open questions of earthquake source dynamics. In the case study of the 2015 Mw 8.3 Chile earthquake, we observed splitting of rupture fronts around the rim of a large barrier. This encircling pattern is analogous to the double-pincer movement in military tactics. Such degree of complexity is previously only seen in simulations and it is observed for the first time in real earthquakes. In the 2018 Mw 7.5 Palu earthquake, we found sustained rupture velocity of 4.1 km/s from the rupture initiation to the end, despite large fault bends. The short or absent supershear transition distance can be caused by high initial shear stress or short critical slip-weakening distance, and promoted by fault roughness near the hypocenter. Steady rupture propagation at a unstable supershear speed lower than the Eshelby speed, could result from the presence of a damaged fault zone.

NEW ADVANCES IN IMPLEMENTING MATERIAL HETEROGENEITY IN THE FINITE-DIFFERENCE MODELLING

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The finite-difference, spectral-element and discontinuous Galerkin methods are the most important time-domain numerical methods in the earthquake and structural seismology and seismic prospecting. A finite-difference time-domain (FDTD) scheme is more than competitive for example for local surface sedimentary structures. It is sufficiently accurate and, at the same time, computationally efficient if it is explicit, heterogeneous and formulated on a uniform spatial grid (the latter does not contradict the use of an efficient discontinuous grid composed of several uniform grids).

Having a scheme explicit and on a uniform grid is relatively easy to achieve in relation to grid dispersion and stability.

Having a scheme heterogeneous and capable of a sub-cell resolution (the necessary condition for efficiency of a uniform-grid scheme) is not trivial. In fact, schemes believed to be heterogeneous had been developed for more than three decades. Those schemes were based on equations for smooth weakly heterogeneous media and could not in principle account for a presence of a material discontinuity.

Moczo and Kristek developed their heterogeneous schemes based on equations which equally applied to smooth and discontinuous heterogeneity and sufficiently accurately accounted for boundary conditions at interfaces. This made it possible to develop schemes with sub-cell resolution and for an arbitrary position and shape of an interface in a uniform grid.

We present recently developed unified discrete representation of strongly heterogeneous media in the elastic, viscoelastic, poroelastic and poroviscoelastic media.

COSEISMIC OFF-FAULT DAMAGE, ITS IMPLICATIONS ON THE RUPTURE DYNAMICS AND BUILDING SEISMIC OBSERVABLES

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Off-fault medium can be damaged due to the stress concentration caused by dynamic earthquake ruptures. The rupture dynamics, radiation and overall energy budget are thus modified by the coseismic off-fault damage because of the feedback from the secondary fracture network. What is the role of co-seismic damage in arresting ruptures? Does co-seismic damage interfere with the rupture with various degrees of geometrical complexity (kinks, step overs, roughness)? And if so, what are the seismic observables (P or S far-field pulse shapes, radiated energy, stress drop. . .) that are indicative of the degree of co-seismic damage? We attempt to address these questions with 2-D dynamic earthquake rupture modelling in planar and geometrical complex faults with and without damage. Preliminary results with a planar finite fault show that the secondary fractures are massively activated around the tip of fault due to the large stress concentration, which sustains the radiation caused by the secondary fractures even after the rupture reaches the edge of fault. For preliminary results with a single kink bent on the extensional side, the rupture propagates on the pre-existing fault without off-fault fractures around the kink. However, for the cases with a kink bent on the compressional side, instead of propagating on the pre-existing fault, a major fault blanch is activated in the direction of conjugate shear failure planes. We further explore increasing degrees of geometrical complexity and produce far-field body-wave pulses to explore the seismic signature of co-seismic damage.

NUMERICAL MODELLING OF SEISMIC WAVE PROPAGATION BY TAKING INTO ACCOUNT 2D NON-LINEARITY EFFECTS IN SUPERFICIAL SOIL LAYERS

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It has long been recognised that the effects of superficial geological layers, or site effects, can play a major role on the seismic ground motion at the free surface. Moreover, soil non-linearity can increase the complexity of wave propagation for strong shaking under particular soil conditions. In this study, we compute wave propagation in a 2-D asymmetrical basin considering both soil non-linearity and pore-pressure effects. Equations of elastodynamics of wave propagation are solved using the spectral element method (SEM). The coupling of vertically propagating waves and the waves specifically generated in 2-D model leads to waves whose amplitude and duration are higher than the 1-D case. This multidimensional impact increases material non-linearity. Such complex wavefield provokes larger deformation and higher pore-pressure rise that cannot be predicted by 1-D modelling. Therefore, our study suggests the use of multidimensional modelling while studying seismic wave propagation in both linear and non-linear complex media.

DOES A DAMAGED FAULT ZONE MITIGATE THE NEAR-FIELD IMPACT OF SUPERSHEAR EARTHQUAKES? - APPLICATION TO THE 2018 MAGNITUDE 7.5 PALU EARTHQUAKE

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The 2018 Mw 7.5 Palu, Indonesia earthquake ruptured 150 km of a strike-slip fault and struck the city of Palu severely. Its impact was amplified by triggering of catastrophic landslides in the proximity of the fault and submarine landslides in the Palu Bay that likely contributed to the devastating tsunamis. Back-projection imaging revealed that the rupture speed rapidly reached a steady state with a sustained velocity of about 4.1 km/s, exceeding the S-wave velocity, V_S . Conventionally supershear ruptures propagate stably at speeds between Eshelby's speed ($\sqrt{2}V_S$) and the P-wave velocity V_P ; the observed speed lies in an unstable regime. Such a low rupture speed was interpreted possibly by the presence of a low-velocity damaged fault zone (LVFZ). In this study, first, we analyse the effect of a LVFZ on rupture development, accounting for the effects of seismogenic width and initial conditions. Furthermore, we investigate the effects of rupture speed and the LVFZ on near-field ground motions. The preliminary results confirm the possibility of an early and steady supershear rupture at the observed velocity due to the LVFZ, and a slower rupture speed results in attenuation of ground motion and thus a reduced landslide risk. Moreover, the LVFZ leads to amplification of near-field ground motion, particularly on the frequency band of 1 - 2 Hz, compared to a homogeneous fault medium with the same rupture speed. Our findings support the significance of rupture and fault zone properties (such as rupture velocity and LVFZ) on near-field ground motion and related landslide triggering.

EARTHQUAKE SEQUENCES ON ROUGH FAULTS: EFFECT OF RESIDUAL STRESS DISTRIBUTION ON SUBSEQUENT RUPTURE

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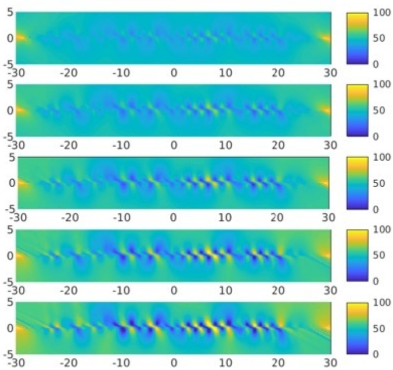
Faults have geometrical disorder at a wide range of spatial scales from planarity (e.g. Candela et al., 2012). Slip on a nonplanar fault causes spatially heterogeneous stress field (Dieterich & Smith, 2009), modulating the style of the next slip event on the same fault. Thus, it is important to investigate rupture dynamics on rough faults in the context of earthquake cycle simulation.

In this study, we model earthquake sequences on rough faults, using a finite difference model which captures inertial dynamics and plastic deformation during dynamic rupture and a quasi-dynamic boundary integral model which simulates the interseismic period. We use the rate and state friction law for the constitutive law on a prescribed rough fault and the Drucker-Prager yield condition for off-fault plastic deformation.

Our preliminary numerical simulations show that the stress field becomes more heterogeneous with accumulating slip (Figure). This highly heterogeneous stress distribution makes the rupture process complicated, such as supershear transition and rupture termination. Later events are more sensitive to the local geometry of the fault due to accumulated stress heterogeneity.



INVESTIGATING THE SOURCE SPECTRUM OF PSEUDO-DYNAMIC RUPTURE MODELS, DERIVED WITH 1-POINT AND 2-POINT STATISTICS

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The omega-square source spectrum has been widely used to describe the basic characteristics of earthquake source (Aki, 1967; Brune, 1970) and to represent the earthquake source effect in stochastic strong ground motion simulation (Boore, 1983; Atkinson and Boore, 2006). The study on the source spectrum has later been extended to finite fault source model (Bernard et al., 1996; Hisada, 2001). Recently, Song et al. (2014) and Song (2016) proposed a pseudo-dynamic source modeling method that considers not only the heterogeneity of main kinematic source parameters such as slip, rupture velocity and slip velocity, but also the correlation structure between them. They set up a probability model for earthquake rupture processes using 1-point and 2-point statistics of the three main source parameters and constructed a statistical input model by analyzing a number of spontaneous dynamics rupture models. In this study, we analyze the source spectrum characteristics of the pseudo-dynamic modeling method. First, we test whether the pseudo-dynamic source models follow the omega-square spectrum if the distribution of source parameters is homogeneous. Then, we analyze the effect of input source parameters on frequency spectrum characteristics. Our preliminary results show that the perturbation of rupture velocity may affect the low frequency band and the corner frequency of the spectrum while the perturbation of peak slip velocity may affect the high frequency band. We plan to extend the analysis further by investigating the effect of auto- and cross-correlations of the source parameters.

RUPTURE MODELS AND IMPLICATION OF RUPTURE DYNAMICS IN SIMULATED GROUND MOTION FOR THE 2016 M7 KUMAMOTO, JAPAN EARTHQUAKE

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We performed simulations of rupture dynamics for a shallow M6.5 crustal earthquake to investigate the implication of multi-scale stress drop spatial variations on rupture dynamics and generation of Strong Motion Generation Areas (SMGA) and Long Period Ground Motion Generation Areas (LMGA) for crustal earthquakes on strike slip faults. Guided by the analysis of the dynamic rupture modeling we propose a kinematic earthquake rupture generator that combines the randomized spatial field approach of Graves and Pitarka (GP) with the multiple asperity characterization approach of Irikura and Miyake (IM) (also known as Irikura recipe). The resulting rupture model incorporates distinct features of both original models. Using several kinematic rupture realizations, we investigated the performance of the proposed, and GP and IM rupture models in simulations of broadband ground motions from the 2016 Kumamoto, Japan earthquake. Finally, comparisons with ground motion prediction equations (GMPEs) were used in sensitivity tests of simulated near-fault ground motion to variations in the prescribed kinematic rupture parameters for the Kumamoto earthquake.

EFFICIENT FINITE DIFFERENCE CODE FOR DYNAMIC STRONG MOTION INVERSIONS

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Dynamic source inversions aim to optimize distributions of dynamic parameters governing the rupture propagation to fit observed seismograms. Due to strong nonlinearity between data and model parameters, employing Monte Carlo methods is advisable. The dynamic inversions thus require fast and accurate solution of the forward problem, mainly the simulation of the spontaneous rupture propagation. We have improved the finite difference staggered grid code FD3D by Madariaga and Olsen [1998], by implementing the traction-at-split method as the fault boundary condition and perfectly matched layers (PML) as the absorbing boundary condition. In addition to the slip-weakening friction law, rate-and-state friction law with strong rate weakening has been also implemented. We test the new code FD3D_TSN on USGS/SCEC benchmarks TPV5 (slip-weakening friction) and TPV104 (fast rate weakening friction) [Harris et al., 2018]. We observe considerable improvements in the accuracy, especially in the case of the heterogeneous prestress. The code has been also ported to GPU using OpenACC directives. The speed-up is approximately 10 times with respect to the CPU version. Moreover, we present two applications of the code: i) dynamic rupture simulations with reduced S-wave speed in the fault zone inducing pulse-like behaviour in accordance with Huang et al. [2014], and ii) dynamic source inversion of the 2014 Mw6.0 South Napa, California, earthquake.

ON THE SUPERSHEAR TRANSITION IN HETEROGENEOUS MEDIA

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During an earthquake, frictional rupture fronts mainly propagate at subshear speed along tectonic faults. However, evidences of supershear propagation have been reported in several occasions. Contrarily to subshear, supershear rupture results in high stresses and particles velocities far away from the interface.

Earthquakes are generally represented as mode II fracture. If the in plane shear load excess a critical value, a crack propagating initially at subshear velocity will transition to intersonic one through the Burrdige-Andrews mechanism. This transition happens at a defined crack size for homogeneous problem. However, realistic interfaces such as geological faults involve heterogeneities, which affect this mechanism. Both in and out plane heterogeneities can facilitate this transition via the emission and reflection of elastic waves. Using numerical methods, it has been shown how the presence of in plane successive weak and strong stripes eases the supershear transition. Front interaction with heterogeneities matters if their size is comparable to the process zone size, in which damage is localized ahead of the crack tip.

In this study, we extend these earlier works to the general case of a dynamic crack propagating along a 2D plane, with various patterns of heterogeneities. Using an elastodynamic boundary integral formulation coupled with a cohesive zone model, we systematically study the interaction of the crack front with the microstructure. Occurrence of supershear transition is extensively investigated for both organized and randomized heterogeneous pattern.

EARTHQUAKE GROUND MOTION SIMULATIONS ON GPU-ACCELERATED PLATFORMS WITH SW4-RAJA

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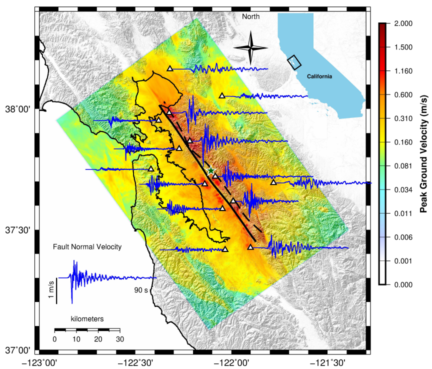
Advances in numerical methods, improvements in rupture models and 3D Earth structure and the inexorable growth of computational power enable higher resolution earthquake ground motion simulations. We are modeling ground motions to frequencies of 5 Hz and higher from large earthquakes (moment magnitude MW 6.5-7.0) on regional scales ($\sim$120 km) using the SW4 4th order summation-by-parts finite difference code. Recently, SW4 was ported to GPU-accelerated platforms (e.g. Sierra, Lassen at LLNL and Summit at ORNL) using RAJA. RAJA is a collection of C++ software abstractions designed to enable architecture portability for mesh-based HPC applications. We show verification of results on different CPU and GPU platforms to machine precision. Porting of SW4 to GPU's greatly improves computational efficiency. We are running site-specific simulations of large ruptures on the Hayward Fault in the San Francisco Bay Area (SFBA). Simulations rely on rupture models from Graves and Pitarka (2016) and a 3D geologic/seismic model from the United States Geological Survey (USGS) including topography. We have shown that simulated motions are consistent with ground motion models, such as those from the PEER NGA-West2 project (Bozorgnia, et al., 2014). In the SFBA, we demonstrate how path- and site-effects in the 3D model bias intensity values and propose a method to account for these epistemic effects in a non-ergodic ground motion model. We have shown how the assumed minimum shear wavespeed in the near-surface geotechnical layer can impact the response.



SURFACE RUPTURE FROM DYNAMIC EARTHQUAKE MODELING

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We perform numerical models of dynamic rupture along faults to study the deeper rupture properties effect, specifically the complex fault geometry, on the dynamic rupture process and the surface rupture patterns. We have studied the surface rupture of the 2013 Mw 7.7 Baluchistan earthquake through dynamic earthquake modeling. Our purpose was to reproduce the observed surface rupture characteristics of this earthquake through the numerical modelling of dynamic rupture, allowing us to better understand the links between the deeper properties of the fault and surface rupture patterns. We have used a dynamic rupture Fortran code based on Boundary Integral Equation Method (BIEM) to simulate spontaneous rupture propagation on faults up to the surface in a homogeneous half-space. The first part of our work was the validation the calculation code using the Southern California Earthquake Center/U.S. Geological Survey (SCEC/USGS) Dynamic Earthquake Rupture Code Verification Exercise. As a first case study, we studied the propagation of the rupture along an inclined thrust fault that breaks the free surface in 2D, testing for variable dip angle of the shallower part of the fault, presence or absence of secondary faults. In order to validate our numerical results, we used the surface rupture and deformation data derived from optical correlation of satellite images. This data set covering 200km of fault rupture trace can be used to derive profiles of surface deformation that we can compare to simulations results. Our results will be displayed and discussed. We will also introduce our 3D fault geometry model used for the 3-D Baluchistan rupture simulations to study the impact of the whole earthquake rupture history and the dynamic stress evolution on the surface rupture patterns.

VARIABILITY IN SYNTHETIC EARTHQUAKE GROUND MOTIONS CAUSED BY SOURCE VARIABILITY AND ERRORS IN WAVE PROPAGATION MODELS

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Numerical simulations of earthquake ground motions are used both to anticipate the effects of hypothetical earthquakes by forward simulation and to infer the behavior of the real earthquake source ruptures by inversion of recorded ground motions. In either application it is necessary to assume some Earth structure that is necessarily inaccurate and to use a computational method that is also inaccurate for simulating the wave field Green's functions. We refer to these two sources of error as "propagation inaccuracies," which might be considered to be epistemic. We show that the variance of the Fourier spectrum of the synthetic earthquake seismograms caused by propagation inaccuracies is related to the spatial covariance on the rupture surface of errors in the computed Green's functions, which we estimate for the case of the 2009 L'Aquila, Italy, earthquake by comparing erroneous computed Green's functions with observed L'Aquila aftershock seismograms (empirical Green's functions). We further show that the variance of the synthetic seismograms caused by rupture variability (aleatory uncertainty) is related to the spatial covariance on the rupture surface of aleatory variations in the rupture model, and we investigate the effect of correlated variations in Green's function errors and variations in rupture models. Thus, we completely characterize the variability of synthetic earthquake seismograms induced by errors in propagation and variability in rupture behavior. The results of this work might be useful in seismic hazard estimation because the variability of the computed ground motion, caused both by propagation inaccuracies and variations in the rupture model, can be computed directly, not requiring laborious consideration of multiple Earth structures.

EARTHQUAKE RUPTURE AND GROUND MOTION MODELING OF THE 2016 CENTRAL ITALY SEISMIC SEQUENCE CONSTRAINED BY BAYESIAN DYNAMIC FINITE-FAULT INVERSION

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The unusual evolution of the earthquake ruptures related to the 2016 Central Italy seismic sequence and the uniquely dense seismological recordings provide an opportunity to better understand the processes controlling earthquake dynamics, strong ground motion, and the relation between earthquakes. We here use initial stress and friction conditions constrained by a novel Bayesian dynamic source inversion (Gallovic et. al., 2019) as a starting point for high-resolution dynamic rupture scenarios. The inferred heterogeneous dynamic models on the planar dipping fault fit very well waveforms recorded at seismic stations. Here we extend the best-fit dynamic source inversion result by taking into account non-planar (e.g. listric) fault geometries, inelastic off-fault rheology, and topography. We utilize the open source software package SeisSol (www.seissol.org) which is specifically suited for incorporating geometrical complexity and high-resolution simulations performed on modern supercomputers. We investigate the effects of including subsequently more realistic modeling ingredients on rupture dynamics and surface ground motions including waveforms at stations that recorded the event. PGV maps show that ground motion amplitudes decreased by about 50 percent on the foot-wall and increased by about 150 percent on the hanging-wall as a consequence of the wave-focusing effect caused by the curvature of the listric fault. However, the effect of the listricity on the PGV is seen only for distances up to 10 km from the fault. Our study thus suggests that the complexity of the fault should not be neglected for the seismic hazard assessment for regions adjacent to active faults.

LONG-TERM INFLUENCE OF FAULT ZONE DAMAGE ON FULLY DYNAMIC EARTHQUAKE CYCLES: CONSTRAINTS ON HYPOCENTER LOCATION AND MAGNITUDE-FREQUENCY DISTRIBUTION

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Mechanical modeling of fault-slip over long timescales is of fundamental importance for understanding earthquake physics and assessing seismic hazard. Mature strike-slip faults are usually surrounded by a narrow zone of damaged rocks characterized by low seismic wave velocities. Observations of earthquakes along such faults indicate that seismicity is highly concentrated within this damaged fault zone. However, the long-term influence of this damaged zone, i.e., decades to hundreds of years, is not well understood. We model aseismic slip and fully dynamic earthquake rupture propagation on a vertical strike-slip fault surrounded by a damaged fault zone for a thousand-year timescale. We use observations along major strike-slip faults, e.g., San Andreas and Calico faults, to constrain the material properties and geometry of the damaged fault zone. These simulations address the effect of fault zone structure and its damage over multiple earthquake cycles along strike-slip faults. We use a spectral-element method in two dimensions with a rate-state dependent friction along the fault to solve the elastostatic and elastodynamic equations of motion. We have implemented shared memory parallelism in Julia to speed up the simulations. Our results show that the presence of the damaged fault zone produces earthquakes with variable magnitudes manifesting a log-linear relationship between the number and magnitudes of earthquakes, i.e., magnitude-frequency distribution. The depth extent of the damaged zone has a pronounced effect on constraining the hypocenter of earthquakes. We also explore the effects of the different damaged fault zone geometries on the magnitude-frequency distribution and hypocenter depths.

COUPLED, PHYSICS-BASED MODELING REVEALS EARTHQUAKE DISPLACEMENTS ARE CRITICAL TO THE 2018 PALU, SULAWESI TSUNAMI

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On September 28, 2018, a Mw 7.5 earthquake struck the North-western part of Sulawesi, Indonesia and induced a localized and sudden tsunami that devastated the Bay of Palu. Devastating tsunamis associated with submarine strike-slip earthquakes are rare, because they displace predominantly horizontally the seafloor. Strike-slip earthquakes can nevertheless source tsunamis, indirectly through landslides or through oblique fault slip. We here suggest that direct earthquake-induced uplift and subsidence could have sourced the observed tsunami within the Palu Bay. To this end, we propose a physics-based scenario of the earthquake tightly constrained by observations, validated against tsunami observations by tsunami and inundation modeling. Our model associates rupture dynamics, seismic wave propagation, tsunami propagation and inundation. The modeled earthquake, featuring sustained supershear rupture propagation, matches key observed earthquake characteristics, including the moment magnitude, rupture duration, fault plane solution, teleseismic waveforms and inferred horizontal ground displacements. In our model, a transtensional stress regime induces up to 2 m of normal slip on a straight fault segment dipping 65^{circ} East beneath Palu Bay, on top of predominant left-lateral slip of up to 6 m. This translates into bathymetry perturbations of about 1.5 m across the submarine fault segment, large enough to trigger a tsunami and to reproduce qualitatively tsunami wave records and field surveys observations. Our results have important implications for submarine strike-slip fault systems worldwide. Physics-based modeling offers rapid response specifically in tectonic settings which are currently underrepresented in operational tsunami hazard assessment.

WHAT DO DYNAMIC RUPTURE SIMULATIONS CONSTRAINED BY GMPEs TELL US ABOUT EARTHQUAKE SOURCE PARAMETERS?

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Dynamic source inversions of individual earthquakes provide constraints on frictional parameters, which are inherent to the studied event. However, general characteristics of the dynamic rupture parameters are not well known. Here we propose to constrain the dynamic rupture parameters by modeling events with waveforms compatible with ground motion prediction equations (GMPEs) using Bayesian inference.

We assume a vertical strike-slip fault governed by the slip-weakening friction law with heterogeneous distribution of dynamic parameters (initial stress, friction drop and characteristic slip-weakening distance). For the dynamic rupture propagation, we utilize finite-difference code FD3D_TSN after Madariaga et al. (1998), further developed by J. Premus. Synthetic waveforms are calculated for a regular grid of phantom stations considering a 1D velocity model. The misfit is evaluated in terms of spectral accelerations at various periods against GMPEs by Zhao et al (2006).

We employ Markov chain Monte Carlo sampling of the dynamic parameter space and obtain a large ensemble of dynamic rupture models with various dynamic parameter settings, whose waveforms statistically fit the observed GMPEs. The synthetic events exhibit various magnitudes and degrees of complexity (e.g., one or more asperities).

We compare stress drops estimated from the corner frequency or source-time-function duration (the so-called apparent stress drop) with stress drops evaluated directly from the dynamic models. We conclude that the empirical apparent stress drop variability is exaggerated by the variability of the corner frequency or duration even without any negative data-processing influence. The variability of the inherent source stress drop is much smaller.

MULTIPLE OBSERVATIONS AND MODELING OF THE TINY GROUND MOTIONS ASSOCIATED WITH COSEISMIC GRAVITY CHANGES

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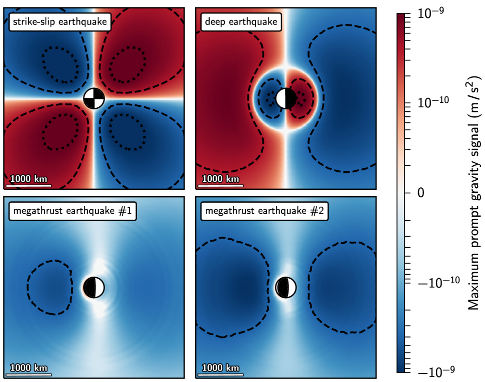
The recent first observations of the prompt elastogravity signals (PEGS) induced by the 2011 Mw=9.1 Tohoku megathrust earthquake generated interest in how these tiny signals might best be observed, especially for lower magnitude events. Simulations of these signals preceding the direct P wave, for different depths and focal mechanisms, first reveal that shallow strike-slip earthquakes offer a better detection potential than subduction megathrust earthquakes. Consistently, clear PEGS are observed at several broadband seismometers during the 2012 Mw=8.6 Wharton Basin earthquake. Due to their short source durations, large deep earthquakes are then shown to have an even larger detection potential, confirmed by the successful seismological observations for the 2018 Mw=8.2 Fiji and 1994 Mw=8.2 Bolivia earthquakes. Detection is even improved when an earthquake is recorded by a number of good-quality seismometers, allowing for stacking techniques. The PEGS of the 2018 Mw=7.9 Off-Alaska earthquake (strike-slip) and of the 2010 Mw=8.8 Maule megathrust earthquake are clearly revealed by such strategies. As a whole, we show new observations of the PEGS for five earthquakes in the [7.9 - 8.8] magnitude range. In all these cases, signals are shown to be accurately modeled when taking into account both the coseismic gravity changes and the ground motions induced by these gravity changes. These findings demonstrate that, even without considering promising future instruments, PEGS detection is not restricted to exceptional events, confirming their potential for magnitude and focal mechanism determination within the few minutes following a large earthquake.



BROADBAND STRONG GROUND MOTIONS ASSOCIATED WITH LARGE SUBDUCTION EARTHQUAKES IN THE GUERRERO SEISMIC GAP, MEXICO

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We present recent results of the simulation of broadband strong ground motions associated with large subduction scenario earthquakes in three dimensions (3D) along the Guerrero subduction zone applying a hybrid approach. This procedure combines a deterministic viscoelastic simulation of ground motions at low frequencies (0.01– 1 Hz) by means of an hp-adaptive discontinuous Galerkin finite-element method (Tago et al., 2012; Cruz-Atienza et al., 2016) with a semistochastic simulation at high frequencies (1-10 Hz) (Pulido and Kubo, 2004). The domain is discretized with a tetrahedral non-structured mesh considering a 3D tomographic model of the Guerrero subduction zone that incorporates the real topography and bathymetry, as well as the geometry of the plate interface. We build broadband wavenumber rupture scenarios based on the estimated inter-seismic coupling that integrates small-scale stochastically-generated source heterogeneities to enhance the radiation of high frequencies following the methodology of Pulido et al. (2015). We set the kinematic source parameters (i.e., slip, rise time, peak time and rupture velocity) by means of a pseudo-dynamic rupture generator that considers the 1-point and 2-point statistics of each source parameter as well as their spatial interdependency extracted from dynamic rupture simulations. We validate our rupture model generator comparing different ground-motion metrics from two moderate-size earthquakes in the region with the median of the corresponding synthetics obtained from several rupture scenarios for each event. To assess the seismic hazard in the region we compute the strong motions for a set of scenario earthquakes and estimate the average durations, peak ground accelerations, peak ground velocities and response spectra maps.

THE DYNAMICS OF ELONGATED EARTHQUAKE RUPTURES

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Both large and small earthquakes develop elongated ruptures with large length-to-width ratios. The energetics of such elongated pulse-like ruptures is radically different from that of conventional circular crack models, but a synoptic understanding of their dynamics is still missing. Here we combine computational and analytical modeling of long ruptures in 3D (mode II and III) to develop a theoretical relation between the evolution of rupture speed and the spatial distribution of fault stress, fracture energy and rupture width. The evolution of elongated sub-shear ruptures is well described by the theoretical rupture-tip-equation-of-motion, which has an inertial feature and depends explicitly on rupture acceleration. The steady energy release rate is limited by rupture width rather than rupture length. For super-shear ruptures, it also depends on rupture speed. The analytic result predicts steady-state supershear ruptures, which are also validated numerically. This inertial effect does not exist in the classical theory of dynamic rupture in 2D unbounded media, but emerges in bounded media or, as shown here, as a consequence of the finite rupture width. Based on the theoretical equation we define the rupture potential, a function that determines the size of earthquake, and we propose a conceptual model that helps rationalize one type of "super-cycles" observed on segmented faults. More generally, the theory developed here can yield relations between earthquake source properties and the heterogeneities of stress and strength along the fault, which can then be used to extract statistical information on fault heterogeneity from source time functions of past earthquakes or as physics-based constraints on finite-fault source inversion and on seismic hazard assessment.

INVESTIGATION OF THE EXTENT OF THE CARIBBEAN SLAB

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The Caribbean is a complex tectonic area including plenty seismic activity and volcanoes and scientists are investigating different features of this region for long time. Magnetic anomalies are absent at plate boundaries of the Caribbean and some of its neighbour plates wherefore it is still unclear how the Caribbean plate formed. Thus, the dimension of the different subduction zones within this area is further debated.
This study investigates the shape and the extend of the different plates subducting in the Caribbean by PP- and SS-wave underside reflections off the 410 km and 660 km phase transitions in the Earth's mantle. Travel times between the main reflection phases (PP/SS) and their precursors ($P^{410}P$, $P^{660}P$, $S^{410}S$, $S^{660}S$) are measured and converted in reflection depths. These values can be interpreted in terms of temperature and composition of the mantle and provide insights into the subduction extend. Within the time period from 2000 to 2018, 20 events with a magnitude $M_w \geq 5.9$ were analysed, showing high quality PP and SS precursor signals recorded in an epicentral distance range of $80° - 160°$. The dataset consists of 82 reflections underneath the Caribbean which densely cover the area of interest by crossing ray paths.
Convergent plate boundaries at subduction zones release the vast amount of seismic energy worldwide. We aim to constrain high-resolution dynamic rupture simulations of the Caribbean region using the ascete framework. To this end we include topography, 3D geological structures, rheology, and fault geometries for earthquake scenarios which can inform tsunami modelling.

ADJOINT INVERSION OF TSUNAMI SOURCE AND ITS APPLICATIONS TO RECENT TSUNAMI-GENIC EARTHQUAKES

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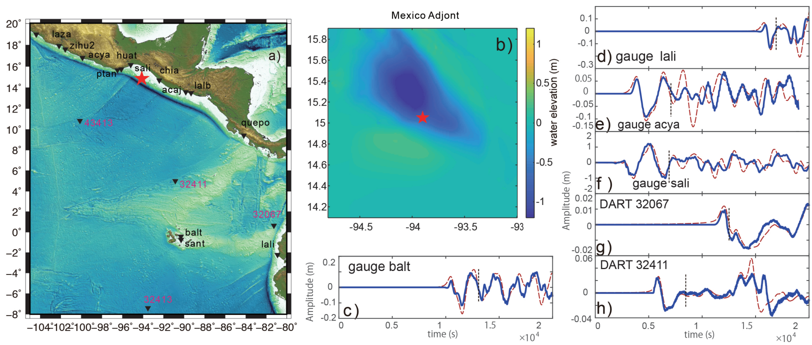
We develop an adjoint-state full waveform inversion procedure to recover the initial water elevation of a tsunami event. Traditional finite-fault tsunami source inversion methods suffer from the uncertainty of fault parameters or crustal rigidity. Moreover, the heavy computational burden of calculating Green's functions results in limited spatial resolution and hinders the real-time applicability of the traditional methods to tsunami early warning. In this work, we apply the adjoint-state full waveform inversion method to the tsunami source inversion. The benefits of the adjoint inversion are two folds: 1) independence of fault parameters, and 2) high computational efficiency, especially for dense tsunami arrays. We valid this approach with synthetic tsunami sources, and apply it to the 2017 Tehuantepec event, the 2014 Chile-Iquique tsunami event and the 2011 Tohoku event. Both synthetic and real-data preliminary results show that the adjoint-state method is of high efficiency and high resolution, outperforming the traditional tsunami source inversions.



EARTHQUAKE MAGNITUDE DEPENDENCE ON HYPOCENTRAL LOCATION ALONG THE SUBDUCTION MEGATHRUST AND ITS IMPLICATIONS

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Different scales of heterogeneities exist on seismogenic faults, including stress distribution and frictional properties. Here, we investigate rupture scenarios considering a variety of heterogeneities along the megathrust interface using spontaneous rupture simulations. We first estimate heterogeneous initial stress distribution from interseismic locking models below Nicoya peninsula, Costa Rica, then initiate spontaneous ruptures at different nucleation points and observe the eventual earthquake magnitudes and slip distribution. We find that $\sim 40\%$ of nucleations tested develop into large earthquakes of $M_w > 7.2$ based on present interseismic locking models. Of these events, those nucleated from deeper depths have a tendency for larger-amplitude shallow slip, suggesting increased tsunami potential. Furthermore, irrespective of the input locking models we do not observe scenario earthquakes with intermediate magnitudes between 6 and 7, a result consistent with observations in Nicoya. Such hypocentre-dependent rupture extents are not only observed in Nicoya, but also in the Cascadia subduction zone, posing challenges in estimating rupture extents from locking models. In addition, when we consider heterogeneous frictional properties on the megathrust, we also find the hypocentre-dependent rupture scenarios. Considering pervasive heterogeneities in nature, the hypocentre-dependent earthquake magnitudes shed lights on understanding foreshock/mainshock observations in certain subduction zones, such as in Tohoku, northeast Japan and Iquique, northern Chile where large foreshocks occurred in a few days before the mainshocks. We interpret why the foreshocks did not rupture larger areas and then could have become the mainshocks is due to their hypocentral locations.

CONSTRAINING COSEISMIC FRICTIONAL PROPERTIES DURING THE 2012 NICOYA M7.6 EARTHQUAKE FROM NEAR-FIELD OBSERVATIONS AND 3-D NUMERICAL SIMULATIONS

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As key elements in earthquake source physics, frictional properties on faults play critical roles in controlling rupture generation and propagation, and thus may significantly impact ground shaking intensities. However, estimation of in-situ frictional properties remains challenging, mainly hampered by inadequate near-field observations and intrinsic trade-offs between parameters. Here, we determine frictional properties on the megathrust ruptured in the 2012 Nicoya Mw 7.6 earthquake by conducting 3-D dynamic rupture simulations with constraints from kinematic source models and records on local GPS network installed on the Nicoya Peninsula. We adopt a linear slip-weakening law in dynamic rupture simulations. Through prescribing a wide range of frictional parameters, we compare the source parameters in our models with kinematic source models and our synthetic surface responses with near-field GPS records. Our best-fit model indicates a low fracture energy $\sim 0.43 \times 10^6 J/m^2$, with an average critical weakening distance of 0.25m and an average strength drop of 3.4MPa. Synthetics in the best-fit model show great consistency with GPS records in static offsets and vertical velocity waveforms. The determined frictional parameters are expected to be further applied in near-field ground motion prediction from spontaneous rupture simulations, thus serving for seismic hazard assessment.

SYSTEMATIC VARIATIONS OF EARTHQUAKE COMPLEXITY FROM CLUSTERING ANALYSIS OF SOURCE TIME FUNCTIONS

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Source Time Functions (STFs) characterize temporal evolution of moment release during earthquake rupture and exhibits tremendous inter-event variations. In this study, we introduce a Dynamic Time Warping (DTW) technique to quantitatively cluster large earthquakes based on the general shape of STFs. We analyze the clustering of STFs from seismic observations, and further relate the results to the rupture dynamics via numerical simulations.

We first apply the DTW clustering to STFs of 3,395 earthquakes (Mw$>$5.5) in the SCARDEC database. The results indicate that the complex STFs correspond to the shallower focal depth and mostly strike-slip mechanism with smaller magnitude, while the simple STFs correspond to the deeper focal depth and mostly thrust mechanism with larger magnitude. We further perform simulations to explore the relation between the STF clusters and rupture dynamics. We produce stochastically self-similar pre-stress distributions and nucleate spontaneous rupture on such heterogeneous faults. This gives us a large population of statistically identical dynamic earthquakes with a wide coverage of magnitudes. We simulate three large earthquake populations with different characteristic slip parameters (Dc) of the slip weakening constitutive relation. The same DTW clustering analysis reveals a systematic pattern that larger Dc tends to produce more earthquakes with complex STFs.

Associated with dynamic simulations, the observed patterns in STF clustering can help to constrain the dynamics of large earthquakes: one possible explanation is the systematic variation of dynamic parameters, such as the depth-varying length scales in different constitutive relations.

EARTHQUAKE MODELING WITH CGFDM: THE RUPTURE DYNAMICS, STRONG GROUND MOTION AND SEISMIC HAZARDS

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The damages caused by earthquakes are becoming more and more serious as the highly developing society. The urgent problems needed to be solved for our country and other earthquake-prone areas are to mitigate the casualties and economic loss. Usually, the large earthquakes which bring intensive damages into the localities occur on faults with complex geometry and other heterogeneous conditions. How to investigate large complex earthquakes by numerical tools is a big challenge task. While keeping the advantages of conventional FDM, e.g. the computational efficiency and the easy implementation, the CG-FDM is also flexible in modeling the complex fault model by using general curvilinear grids, and thus is able to model the rupture dynamics of a fault with complex geometry, such as oblique dipping fault, non-planar fault, fault with step-over, fault branching, even if irregular topography exists. In this work, we use this numerical method to model the dynamic rupture, the strong ground motion and then the seismic hazards distributions of large earthquakes. A typical example is the Tangshan earthquake modeling run on TaihuLight. With support from supercomputers, this physics-based earthquake modeling can help us to investigate large destructive earthquakes and to predict seismic hazards for earthquake scenarios.

L I S T S

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