Faculty of Mathematics, Physics and Informatics, Comenius University Bratislava

and

Geophysical Institute, Slovak Academy of Sciences, Bratislava

Workshop on

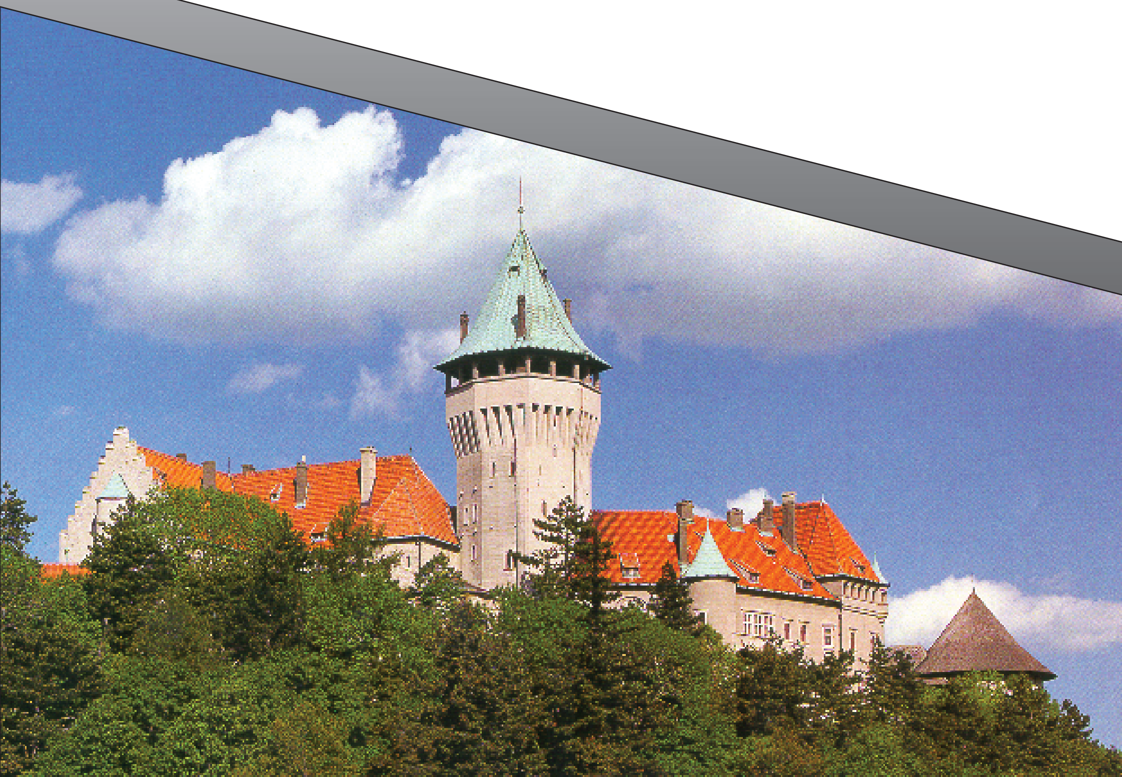
Earthquake Source Dynamics: Data and Data-constrained Numerical Modeling

2010 ESD

Proceedings of the Workshop - Abstract Book

June 27 – July 1, 2010

Smolenice Castle, Slovak Republic



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ABSTRACT BOOK

http://www.nuquake.eu/ESD2010/

SLOVAK RESEARCH
AND DEVELOPMENT
AGENCY

This workshop was supported in part by the Slovak Research and Development Agency under the contract No APVV-0435-07 (project OPTIMODE)

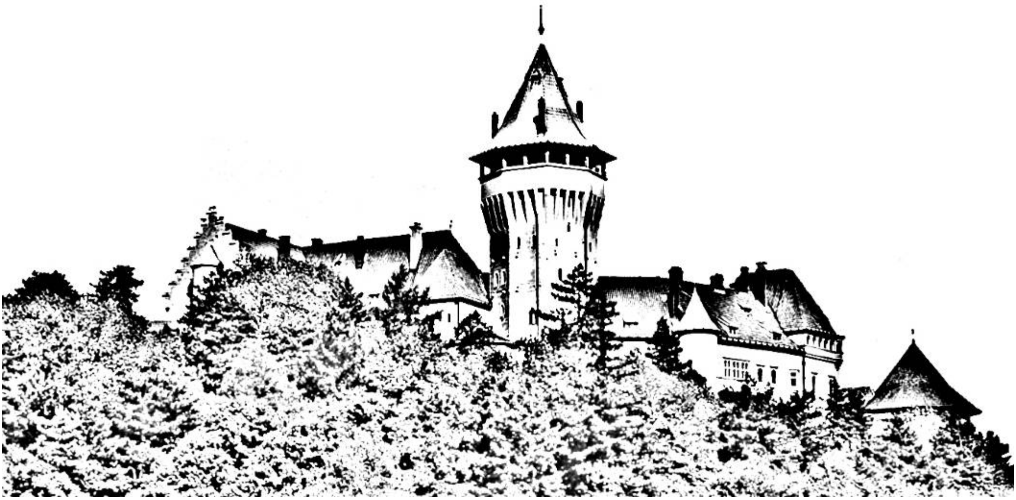
Editors: Ralph J. Archuleta, Peter Moczo, Jozef Kristek, Martin Galis

Comenius University Bratislava
Published by FX, s.r.o., Bratislava

ISBN: 978-80-89313-49-5

CONTENTS

A B S T R A C T S



CONSTRAINING THE DEPTH DEPENDENCE OF FAULT CONSTITUTIVE PARAMETERS IN SPONTANEOUS RUPTURE MODELS

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I investigate constraints on the depth dependence of fault-constitutive parameters in dynamic spontaneous rupture models using a wide variety of geophysical data. Seismological observations constrain the spatial and temporal characteristics of slip in earthquake ruptures. Geodetic observations constrain the spatial characteristics of slip in earthquakes as well as the inter-seismic strain accumulation. Laboratory experiments offer empirical relationships for friction as a function of slip, slip rate, and state variables. Geologic and geophysical observations indicate confining pressure increases with depth, but dynamic sliding occurs on slip surfaces a few millimeters wide at a low stress level, consistent with measurements of minimal heat flow. I use a combination of Burridge-Knopoff slider-block models and finite-element spontaneous rupture models to bound the depth dependence of parameters in some widely-used fault constitutive models (e.g., slip-weakening and rate- and state-friction). The slider-block models permit calculating the long-term or steady-state depth variation in relative and absolute stress for a given set of model parameters, and the finite-element models are used to confirm the trends found in the slider-block models.

A HIERARCHY OF TREMOR MIGRATION PATTERNS EXPLAINED BY THE INTERACTION BETWEEN BRITTLE ASPERITIES MEDIATED BY CREEP TRANSIENTS

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Coupled slow slip and tectonic tremor phenomena offer an exceptional opportunity to investigate the rheology of faults at depth. Tremor activity might provide a natural creepmeter to monitor aseismic slip with high resolution, including possible precursory slip associated with the nucleation of large earthquakes. Recently, a hierarchy of tremor migration patterns has been observed in Cascadia. On the longest time scales tremor migrates alongstrike at a speed of 10 km/day, coincident with the propagating front of a slow slip pulse. At shorter time scales tremor swarms coined “rapid tremor reversals” (Houston *et al.*, 2010) propagate backwards along-strike into the slow slip pulse at 100 km/day. At even shorter time scales tremor streaks propagate along-dip at 1000 km/day (Ghosh *et al*., 2010). Whereas the largest scale migration pattern is naturally explained by triggering of tremor by a propagating slow slip pulse, the origin of the two other patterns is still unknown. I propose a unifying framework to understand these three patterns and their relation to the slip rate distribution within the slow slip pulse. Numerical models of tremor generated by brittle asperities present in the deep, mainly ductile portions of a fault reveal that migrating tremor swarms arise from a cascade of triggering between asperities mediated by propagating creep perturbations. The speed of these creep waves controls the tremor migration speed and depends on the background slip rate. Larger slip rates at the leading front of a large scale slow slip pulse produce faster tremor migration, slower slip within the pulse implies slower tremor migration. The model yields further predictions that could be tested by observations affordable in the near future.

TOWARDS EARTHQUAKE SOURCE IMAGING BY A SPACE-BASED STRONG MOTION SEISMOMETER

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Seismology urgently needs data that can enable robust source imaging. An ideal dataset consists of spatially unaliased recordings of ground motions at a spacing of at most half a wavelength. Building and operating a seismic network with spatial sampling of 100 m to 1 km to resolve waves up to 1 Hz would be extremely costly and challenging. We are exploring the feasibility of an alternative system, a "space seismometer". We estimate that a geosynchronous satellite optical telescope with 4 to 10 m aperture could deliver 1 Hz, 100 m, 1 cm/s resolution in time, space and ground velocity amplitude, respectively, over 300x300 km large areas. To assess the gain in source imaging capabilities that such data could allow, we analyzed synthetic M7 earthquake scenarios in Southern California. The scenarios were generated by spectral element simulations and included sub-Rayleigh and super-shear ruptures, ruptures with and without surface break and ruptures with varying number of asperities. The ground motions were submitted to the noise generated by the proposed optical measurement and image processing chain. Important aspects readily inferred by visual inspection or straightforward data processing include the presence of Mach cones, diagnostic of supershear rupture, and the spatio-temporal complexity of shallow slip. Inferring sub-surface slip requires solving an immense source inversion problem. Short of a scalable source inversion code we attempted a time-reversal imaging technique. We were able to retrieve gross features of sub-surface slip but encountered specific problems related to defocusing and incomplete coverage. These can be addressed by an iterative adjoint inversion approach including constraints from seismic data at regional and teleseismic distances.

A KINEMATIC SLIP INVERSION METHOD INCLUDING UNKNOWN SOURCE FAULT GEOMETRY BY STRONG MOTION DATA

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Many previous studies succeeded to obtain precise slip distributions of large earthquakes from strong motion and other seismic and geodetic data set. Though the geometry of source fault is also known to be important for near-source strong ground motions (e.g., Iwata *et al.*, 2000; Gallovic *et al.*, 2010), most of source inversion studies assumed one or plural planar fault planes. In order to include effects of fault geometry on near-source ground motions, we are trying to extend a method to invert slip distribution simultaneously with its fault geometry. It is applied to the dataset of the 2008 Iwate-Miyagi Nairiku earthquake.

At the first step, a linear source inversion (Hartzell and Heaton, 1983) is carried out assuming a planar fault model. That is, all the subfaults have same strike and dip angles as in conventional source inversions. At the second step, the fault geometry is represented by strike and dip angles at some control points distributed on the fault. The strike and dip angles at each subfault is calculated by bilinear interpolation. Then, strike and dip angles at control points and slip amounts at each subfaults are iteratively solved from the same data set by the nonlinear least-squares method starting from the solution of the first step as the initial model. The velocity structure model is constructed through waveform modeling for a moderate aftershock following Asano and Iwata (2009).

The result shows that the strike angle of the asperity is almost same as the MT solution. But dip angles at shallower portions of the fault tend to be smaller than the MT solution, and the strike angle is estimated to be rotated northwestward in the northern part of the fault. These features appear to be consistent with aftershock distribution.

ENERGETIC AND ENERVATED EARTHQUAKES: REAL SCATTER IN APPARENT STRESS AND IMPLICATIONS FOR GROUND MOTION PREDICTION

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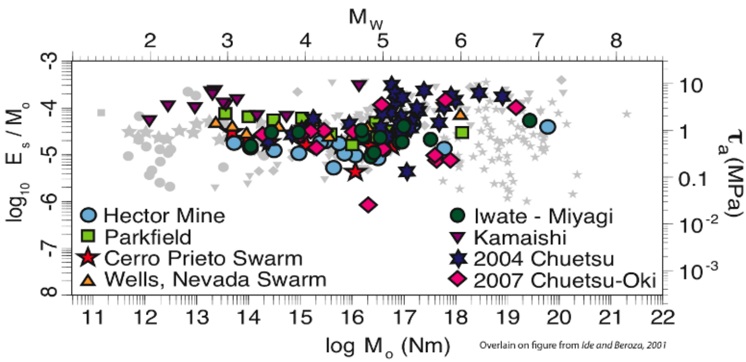
We estimate scaled seismic energy and apparent stress to explore the relationship between radiated seismic energy and moment. Our empirical Green's function method uses time-averaged coda spectra, to exploit the stability and averaging effects of the seismic coda. In each region, we choose events that are nearly co-located so that the path term to any station is constant. Small events are used as empirical Green's functions to correct for propagation effects. For eight sequences in the western US, Mexico and Honshu, Japan, over 8 orders of moment, we find that the apparent stress averages to 1 MPa for most events, with scatter between particular events and sequences. Overall, our results support earthquake self-similarity, and are consistent with studies of radiated energy determined from other methods. In particular, we identify several earthquakes in the magnitude range of M_w 4.5 to M_w 5.5 in Japan that have anomalously high and low apparent stress, as high as 10 MPa and as low as 0.02 MPa. We investigate the source of these energized and enervated earthquakes, their spectra, and accelerations they caused. The enervated events are depleted in high frequencies compared to regular events of similar size, while the energetic events are enhanced in higher frequencies. These earthquakes highlight the fact that real variations in apparent stress exist, even though the average event may have a constant apparent stress. Comprehending the nature of these anomalous events will aid in the understanding of the origin of high frequency ground motion and extreme ground motion prediction.



SIMULATIONS OF SLIP HISTORY ON FAULTS WITH HETEROGENEOUS RATE-WEAKENING AND RATE-STRENGTHENING PROPERTIES

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Variations in friction are thought to be an important factor in controlling the magnitude and the long-term timing of events in an earthquake cycle. We investigate the influence of large variations in frictional properties on the rupture of individual earthquakes and the long-term apparent strength of faults. Recent findings of the SAFOD experiment on the San Andreas fault revealed the presence of fault minerals with velocity-strengthening behavior at aseismic slip rates and low static friction coefficients. Such materials tend to creep in the interseismic period with low prestress and hence could promote the overall fault failure at such low stresses.

Geological and geophysical studies indicate that mature crustal faults are weak compared to laboratory measurements of static frictional strength, in that they operate under much lower average shear stresses. We would like to test the hypothesis that the apparent low strength of faults is fully or partially due to spatial variations in frictional properties of fault rocks. To that end, we consider models of earthquake cycles with dynamic ruptures that include statically weak areas with velocity-strengthening friction neighboring statically strong areas with velocity-weakening friction. The fault is governed by a rate- and state-dependent friction law. We will report on our efforts to systematically explore the behavior of such models and to identify the parameter regime that allows such faults to be weak, i.e. to operate under low overall shear stress. One of our goals is to determine whether faults with heterogeneous properties can be weak in the absence of seismically activated dynamic weakening mechanisms, or whether dynamic weakening would be required.

STRESS HETEROGENEITY IN A DYNAMIC RUPTURE PROPAGATION WITH STRONG VELOCITY WEAKENING FRICTION

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Recent high-speed friction experiments and theoretical studies (e.g. Beeler *et al.*, 2008; Rice, 2006) suggest strong velocity weakening, with dramatic reduction of the dynamic friction coefficient. These studies are associated to thermal weakening mechanisms that may prevail in nature (Rice 2006). In addition, it is expected that initial stress on faults prior to rupture is highly heterogeneous in nature, as suggested by source images resulted from kinematic inversion of real earthquakes. Therefore it is relevant to study earthquake under these conditions.

In the present work we asses the role of stress heterogeneity on rupture dynamic governed by a rate and state friction law with strong velocity weakening. The problem is tackled in a 2D in plane mode using the staggered grid split node (SGSN) finite differences (FD) testing code developed by Day, (2009). Our model strategy consists first on the development of rupture simulations under different uniform prestresses that produces, respectively, cracklike, pulselike and dying rupture propagation. Then, these three ruptures mode are perturbed incorporating stress heterogeneity, enhancing and reducing the pre-stress at localized patches in which the rupture mode is well defined. We evaluate the sensitivity of the macroscopic parameters (rise time, rupture speed, peak slip rate and final slip) to the level and patch length of the perturbed pre-stress.

WHAT CONTROLS THE LOCATION WHERE RUPTURE NUCLEATES IN LARGE EARTHQUAKES? SOME INSIGHTS FROM THE 1999 TURKISH EARTHQUAKES

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Ten years after the devastating Turkish earthquakes of Izmit and Duzce, we review several sets of observations which show that the location of the epicenters of the two shocks obeys some mechanical logic. The Izmit epicenter is located where the North Anatolian Fault crosses a nest of small earthquakes. Events in this swarm, known to be active since earthquakes are recorded in this area, are mostly characterized by normal faulting and show a direction of extension N10E (Crampin *et al.*, 1985), nearly perpendicular to the local EW strike of the NAF. Shear wave splitting measurements in this area (Evans *et al.*, 1987) show the presence of strong crustal anisotropy interpreted as indicative of the presence of numerous parallel fluid-filled vertical cracks displaying a N10E tensional stress direction. These observations show that the epicenter zone of Izmit was, before the earthquake, the sit of intense on-going extension in a direction nearly orthogonal to the strike of the NAF, thus releasing the normal stress on the NAF in the area and facilitating rupture nucleation. Three months after Izmit, the Duzce earthquake extended the 150km long Izmit rupture 40km eastward. The Duzce epicenter, located about 25km from the end of the Izmit rupture, is precisely near the start of the simple linear segment of the fault (Pucci *et al*., 2006) where supershear rupture occurred (Bouchon *et al.*, 2001). Aftershock locations (Milkereit *et al.*, 2000) show that Duzce, at its start, was the first significant Izmit aftershock to occur on this simple segment. The three months delay between the two earthquakes may represent the time of aftershock diffusion across the geometrically complex western segment of the Duzce fault.

TOWARDS A VIRTUAL LOWER RHINE EMBAYMENT

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We show results of an ongoing project that aims at understanding the earthquake interactions within fault networks in order to improve seismic hazard estimations with application to the test region of the Lower Rhine Embayment, Germany. Seismic risk and hazard estimates mostly use pure empirical, stochastic models of earthquake fault systems tuned specifically to the vulnerable areas of interest. Although such models allow for reasonable risk estimates, such models cannot allow for physical statements of the described seismicity. Here we present results obtained by a quasidynamic fault model based on rate- and state-dependent friction. Faults are represented by a finite number of patches, each of which is allowed to independently be in (1) locked, (2) nucleating, or (3) earthquake state. We show results for a few test-cases with two faults as well as for a recent extensional fault model of Lower Rhine Embayment that comprises sixteen normal faults. We analyze the spatial and temporal clustering of events and characteristics of system dynamics by means of physical model parameters. We compare our results with those obtained by a stochastic simulator with tectonic loading and stress-interactions, characterized by quasi-periodic recurrence of characteristic on-fault events, background activity with a power-law distance decay relative to the faults, and epidemictype aftershock triggering.

EXTENDED FINITE ELEMENT METHODS FOR RUPTURE SIMULATION ON NONPLANAR FAULT SYSTEMS

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Currently, both lithostatic deformation and dynamic earthquake rupture simulations under standard FEM are limited by the complexity of fault networks, as generating meshes that both conform with faults and have appropriate properties for accurate simulation is an unsolved problem. Complicating this is the fact that fault geometry is not well known; robustness of solution to fault geometry must be determined. Remeshing with varying geometry is simply not computationally feasible under current mesh generation/finite element approaches. The extended finite element method (XFEM) provides a natural way to incorporate strong and weak discontinuities into discretizations. It alleviates the need to mesh discontinuities, allowing simulation meshes to be nearly independent of discontinuity geometry. The XFEM makes a natural choice for discretization in dynamic rupture simulations on complex fault systems. We develop a method based upon the XFEM using Nitsche's method to apply boundary conditions, enabling the solution of static deformation and dynamic earthquake models. We demonstrate the method with two, two-dimensional problems: a SCEC code verification benchmark and simulations on surface traces of the Community Fault Model of Southern California.

SUPERSHEAR MACH-WAVES EXPOSE THE FAULT BREAKDOWN SLIP

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Mikumo *et al.* (2003) showed that it is possible to estimate the breakdown slip (D_c) as the slip at the time of the peak slip rate for rupture propagation with subshear speeds. Cruz-Atienza *et al.* (2009) later attempted to extend this method to estimate D_c as the displacement at the time of the peak particle velocity from seismic strong-motion records. However, a reasonably accurate estimate of D_c was only possible in a narrow zone adjacent to the fault (typically on the order of hundreds of meters) due to the fast decay of the seismic energy related to the stress breakdown process. When the rupture propagates with supershear-speeds, this energy is carried much farther away from the fault by Mach waves, in particular Rayleigh Mach waves when rupture reaches the Earth's surface. Here, we present a new approach to estimate D_c from strong-motion records containing Mach waves (Cruz-Atienza and Olsen, 2010). First, we show that the method by Mikumo *et al.* is valid for supershear rupture propagation. This method is then used to estimate D_c via an asymptotic approximation of the slip and slip-rate time histories from the Mach waves. Using spontaneous rupture simulations we demonstrate that, for a visco-elastic half-space model, D_c can be estimated with an accuracy of ~40 % from Mach waves that have propagated a distance of at least 3 km from the fault. The method is applied to estimate D_c for the 2002 M_w 7.9 Denali, Alaska, earthquake (~1.5 m) and for the 1999 M_w 7.6 Izmit, Turkey, earthquake (~1.7 m).

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NUMERICAL MODELING OF EARTHQUAKE RUPTURE IN LARGE ASPECT-RATIO FAULTS

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Large earthquake with large aspect-ratio faults such as the 2002 M_w 7.9 Denali and the 2008 M_w 8.0 Wenchuan earthquake in China, both with fault length about 300 km, open questions on how rupture operates at such as large scale, why rupture extends so long, and what are the conditions to rupture stops before it becomes a large event. To address these questions, large-scale simulations are needed. We initiate the investigation in this direction. We started our modeling with simple vertical faults of 400 km length in both strike-slip and dip-slip faulting. Homogeneous initial stress and embedded fault was assumed. First we want to investigate the role of the width (*W*) of the fault. Parameterization of stress and frictional properties follows the TPV3 problem described in the SCEC benchmark problem.

Our numerical investigation shows that *W* takes an important role on rupture arresting and the generation of steady-state pulse-like rupture in strike slip as well as dipping faults. In strike slip, in which in-plane is dominant, rupture is arrested in small Ws faults (5.9km) due to the reflecting S waves coming from the top and bottom of the fault (stopping phases). For larger W_s, the rupture propagation becomes self-sustained, increasing the rupture speed with increasing *W*. Interestingly, the slip-rate, from self-sustained rupture models, becomes a steady-state pulse, i.e., the slip-rate pulse travels without altering its shape and amplitude. In dipping faults, in which the anti-plane mode is dominant, the same phenomenon is observed, but the effect of *W* is stronger than in strike slip faults. Rupture arresting extends to larger W_s (8km) due to, in this case, the presence of two stopping phases, associated with the P and S waves (see also poster from Huang *et al.*).

NUMERICAL INVESTIGATION OF THE LONG-TERM SEISMIC CYCLE IN GEODYNAMIC SIMULATIONS OF A SUBDUCTION ZONE

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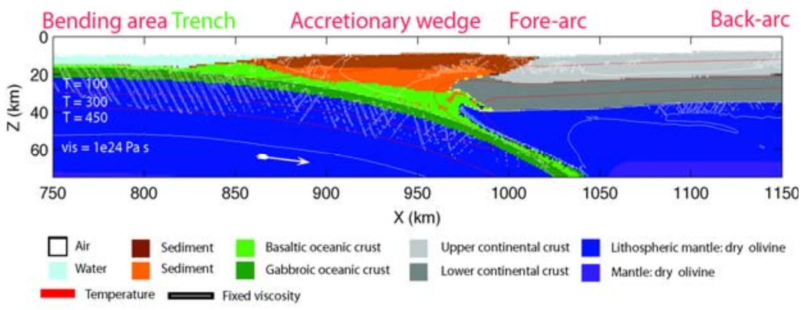
Earthquakes occur over different spatial and temporal scales. While abundant data are available to help understand short-term behavior of earthquakes, the long-term evolution of subduction zone seismicity remains elusive due to the limited observational time span. Realistic numerical modeling of subduction zone physics can help to improve our understanding of the long-term seismic cycle. The objective of this study is to quantify seismic observations in this geodynamic model for comparison to nature. We use a plane-strain, coupled petrological and thermo-mechanical finite-difference scheme with marker-in-cell technique to solve the conservation of momentum, mass, and energy for a visco-elasto-plastic rheology (I2ELVIS). In a 1500x200 km2 model a generic oceanic plate subducts below a continental overriding plate, spontaneously generating localizations of plastic strain when the second invariant of the deviatoric stress tensor exceeds the Drucker-Prager yield stress. The geodynamic models show several spontaneously formed clusters of plastic strain localizations (Fig. 1) whose activity is coupled through the thrust interface. Periodicities in these models reach 20.000 years or more. Within the localization zones, we observe sudden drops in stress simultaneously with strong increases in strain rate that we use to define slipping events. For these, we build a seismic catalog, including an event-size indication. Preliminary results have shown the occurrence of slow events with heterogeneous slip over lengths up to 56 km in the thinnest portion of the basaltic crust. Our final target is to identify events on the verge of slipping, transfer the stress field to a dynamic model for a full spontaneous rupture and then back for a complete modeling of the earthquake cycle.



HIGH FREQUENCY GROUND MOTION FROM SPONTANEOUS RUPTURES ON ROUGH FAULTS

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A particularly challenging aspect of generating synthetic broadband seismograms is to accurately capture, in a single model, both the coherent low frequency wavefield and incoherent high frequency radiation. Toward this end, we seek to identify the fundamental source processes responsible for exciting high frequency waves and incorporate these processes directly into spontaneous rupture models. Our present focus is on fault roughness, which we investigate using a newly devised high-order finite difference method featuring strongly rate-weakening fault friction and off-fault plasticity. The latter tames otherwise unreasonable stress concentrations and prevents fault opening. Natural fault surfaces exhibit slight deviations from planarity with amplitude-to-wavelength ratios of roughness between 10^{-3} and 10^{-2}. Such roughness exists at all scales, providing a means of exciting waves of all frequencies. Production of high frequency radiation depends not only on fault roughness, but also on the proximity of the prestress state to the critical conditions at which self-sustaining propagation is just barely possible. Around these conditions, even slight perturbations in the fault profile induce large fluctuations in rupture velocity and the efficient production of high frequency waves. Synthetic seismograms share numerous features with actual strong motion data: an approximately flat acceleration spectrum at high frequencies and nonstationarity of frequency content as a function of time (i.e., a shift toward longer periods later in the record, which we explain in terms of a Doppler shift as the rupture recedes from the station).

CONSTRAINTS ON EARTHQUAKE DYNAMICS FROM OBSERVATIONS IN THE NEAR-SOURCE REGION AT THE SAN ANDREAS FAULT OBSERVATORY AT DEPTH

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The deployment of instrumentation deep within the San Andreas Fault has opened a new window for the study of the earthquake source by reducing the distance between source and receiver to a few hundred meters or less. Key questions that can be addressed in the near-source region include scaling of apparent stress, static stress drop, dynamic stress drop, the minimum size of earthquakes, and potentially the time, length and displacement scales of frictional evolution during nucleation. Seismometers in the SAFOD main hole record earthquakes down to the detection threshold of M_w −3.5 (at 150 m distance). Earthquake source parameters determined using a variety of methods indicate that there is no breakdown in apparent stress or stress drop scaling for $M_w \geq -1$. The highest values are comparable to the laboratory-derived frictional strength of faults. The smallest events have source dimensions < 1 m, indicating that if there is a minimum earthquake size, it must lie at even lower spatial scales. The rate of fault weakening can also be studied using the earliest part of the P-wave arrival by using Kostrov's [1964] model for self-similar crack growth to determine the dynamic stress drop. These earthquakes begin abruptly with the dynamic stress drop typically reaching 5 MPa within the first few milliseconds of rupture, pointing to a very small slip weakening length scale. The absence of a slow initial phase of the type described by Iio [1995], the rapid release of stress when the rupture is 1-2 m in dimension, and the agreement between the early dynamic stress drop and static stress drop all point to slip weakening distance over which friction evolves from static to fully dynamic measured in 100's of microns, comparable to values measured in the laboratory.

FOCAL MECHANISMS OF MICRO-EARTHQUAKES IN SEISMOACTIVE AREA IN THE MALÉ KARPATY MTS., SLOVAKIA

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We have analyzed 44 micro-earthquakes with magnitudes between 1.2 and 3.4, which occurred in the Dobrá Voda area, Slovakia, in the period of 2001-2009. The epicenters of the micro earthquakes form a cluster elongated in the ENE-WSW direction. The depths of the hypocenters vary from 1 km to 14 km. Three different methods were used to calculate the focal mechanisms: (a) a method using the polarities of Pg and Pn waves, (b) the P-wave amplitude inversion of moment tensors, and (c) the waveform inversion of moment tensors. All three methods show similar double-couple parts of the focal mechanisms. The majority of the analyzed micro-earthquakes have a left-lateral strike-slip focal mechanism with weak normal or reverse components. The full moment tensors comprise significant non-double-couple (non-DC) components. The non-DC components are partly numerical errors of the inversion but might be also of a physical origin. The most accurate values of the non-DC components are obtained from the P-wave amplitude inversion. For this inversion, the isotropic component (ISO) and the compensated linear vector dipole component (CLVD) are mostly positive and well correlated. This might indicate tensile faulting. Adopting the model of tensile faulting, we estimated the mean ratio of P to S wave velocities in the focal area from the values of ISO and CLVD, v_P / v_S = 1.5 -1.6.

KINEMATICS OF THE DOUBLE-LAYERED DIPPING FAULT RUPTURE DURING THE 2008 WENCHUAN EARTHQUAKE

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The 2008 Wenchuan earthquake has a double-layered dipping fault rupture from the investigation of surface fault scarps. At southwestern part of the double dipping fault zone, there was a joint vertical left-lateral fault perpendicular to the dipping faults called Xiaoyudon Fault. To investigate how these coseismic fault slips were created along such complicated fault geometry, we conducted a forward modeling of kinematic slips to explain the near-fault strong motion records. We first constructed a fault model based on the surface fault traces and InSAR fault models. It consists of three planar faults, F1 (SW Beichuan Fault), F2 (Xiaoyudon Fault) and F3(Pengguan Fault +NE Beichuan Fault). Strike dip and rake angles, length, width and upper western location are as follows: F1: (N223E, 50, 135), (130km, 45km), and (30.82N, 103.28E). F2: (N131E, 90, -28), (10km 19km), and (31.23N, 103.72E). F3: (N222E, 37, 90), (206km, 35km), (31.01N and 103.28E). It should be noted that northeastern fault segments are omitted in this modeling. Based on the above fault model, we computed near-fault ground motions assuming the hypocenter location of (31.061N, 103.333E, 17.3km). We used the discrete wavenumber code (AXITRA). We assumed a static slip distribution estimated by InSAR analysis and try to investigate the rupture propagation pattern by a trial and error way. Unfortunately, as the accelerograms did not have accurate timing, we could not perfectly constrain the rupture scenario of this earthquake, but we could propose some possible scenarios for this earthquake to explain the observed waveform paradox based on our proposed fault model.

Acknowledgments: Digital accelerograms were provided by the National Strong Motion Observation Network System (NSMONS) of China.

SELF-SIMILAR BEHAVIOR OF PULSE-LIKE DYNAMIC RUPTURES IN ELASTIC AND PLASTIC MEDIA

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From seismic inversions earthquake ruptures are found to show dominantly pulse-like behavior, i.e. the fault heals shortly behind the rupture front leading to short rise times. In numerical simulations with strong velocity-weakening friction, ruptures occur in pulse-mode under certain initial conditions. Such friction-models are considered realistic from recent laboratory experiments with high slip rates. However, the dynamics of rupture pulses remains elusive. High stress concentrations at the rupture front may generate inelastic off-fault response leading to increased energy absorption. Off-fault inelasticity thus plays an important role for realistic predictions of near-fault ground motion. For steady-state pulses analytical relations between cohesive zone properties, background stresses, fracture energy and rupture speed are available, but do not account for the energy dissipated by off-fault anelastic processes.

We apply the 2D spectral element method (SEM2DPACK of Ampuero, 2008) to model spontaneous rupture under strong velocity-and-state-dependent friction with off-fault Coulomb plasticity in a 2D in-plane model. The behavior of the generated rupture pulses approaches one of distinct areas of self-similarity. We characterize these areas and the transitions between self-sustaining pulse-like rupture, decaying pulses and crack-like ruptures in dependence on background shear stress and nucleation energy. Fine nucleation tuning is required to obtain steady-state pulses. For given background stress the asymptotic self-similar behavior seems independent of the nucleation conditions. Furthermore, we quantitatively analyze the contribution of the induced off-fault energy dissipation to the rupture energy balance and resulting macroscopic features of the earthquake.

3D RUPTURE DYNAMICS WITH UNSTRUCTURED SPECTRAL ELEMENTS AND A FLUX-BASED FAULT SOLVER

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An important goal of computational seismology is to simulate earthquake dynamics and strong ground motion in realistic models that include crustal heterogeneities and complicated fault geometries. The goal of this work is to integrate rupture fault dynamics into the 3D open source spectral element (SEM) code SPECFEM3D-SESAME, the latest version of SPECFEM3D, which provides high flexibility in meshing complex media. Unstructured meshes of hexahedral elements are generated by CUBIT, a general purpose state-of-the-art mesh generation software. Our implementation follows the principles introduced by Ampuero (2002) and Kaneko *et al.* (2008). We will report on the results of this new code applied to some of the SCEC 3D Code Validation benchmarks. Numerical methods for earthquake dynamics are prone to high frequency spurious oscillations that can contaminate the rupture propagation in low resolution simulations. This issue is exacerbated in SEM because the method has no intrinsic damping. A usual technique to overcome this problem is the introduction of artificial Kelvin-Voigt damping in the bulk. However, this degrades stability and implies very small time steps in simulations with complicated geometries. Recently, De La Puente *et al.* (2009) introduced a dynamic fault solver in a Discontinuous Galerkin method (ADER-DG).Their results show very low spurious artifacts. We attribute this to the intrinsic, high-order damping emerging from the space discretization with fluxes. We will present a hybrid formulation in which we treat the fault boundary conditions with numerical fluxes but solve the wave propagation in the bulk with the more computationally efficient SEM.

HYBRID MULTIDOMAIN FINITE ELEMENT AND BOUNDARY ELEMENT METHOD FOR DYNAMIC RUPTURE IN HETEROGENEOUS MEDIA

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We have recently developed a coupled domain finite element (FEM) and boundary element method (BEM) for modeling dynamic rupture in an elastic medium. This method can be used to solve efficiently spontaneous rupture problems in heterogeneous media, but it is restricted to the case in which the rupture surface is contained within a homogeneous portion of the domain. In the present work we present an alternative multidomain coupled FEM-BEM approach that removes this limitation, and allows us to treat faults within an arbitrary heterogeneous medium, including faults at the interface between two different materials, single or multiple faults that cross several different materials, and breaking faults. The method is based on a coupled multidomain boundary integral formulation within the vicinity of the fault, and a domain finite element formulation farther away from the fault. This hybrid approach allows us to exploit the advantages of each method—the good quality approximation of the BEM near singularities and stress concentrations and the simplicity and versatility of the domain FEM. We illustrate the applicability of the method with several antiplane examples in a halfplane, including one in which an oblique breaking fault is located at the interface between two different materials.

SIMULATION OF SPONTANEOUS RUPTURE BASED ON A COMBINED BOUNDARY INTEGRAL EQUATION METHOD AND FINITE ELEMENT METHOD APPROACH

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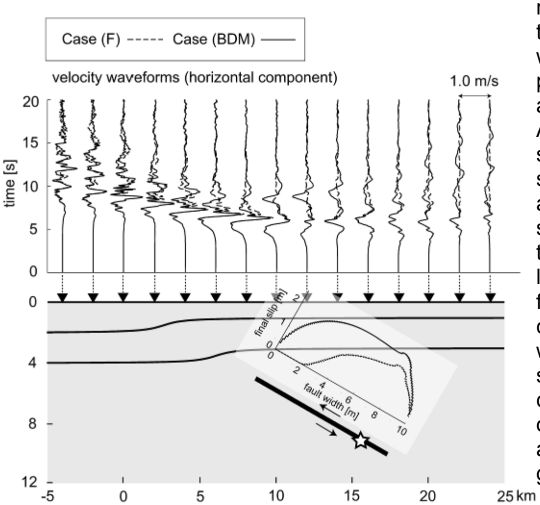
We present a hybrid approach for solving the dynamic rupture problem in an elastic medium. It combines the advantages of the boundary integral equation method (BIEM), which is capable of representing accurately the solution near a crack tip, with those of the domain finite element method (FEM), which can handle conveniently heterogeneous materials, as well as the traction-free condition on a free surface and the continuity of traction across interfaces. When applied jointly, the proposed BIEM-FEM can be used to solve efficiently spontaneous rupture problems in heterogeneous media, provided the rupture surface is contained within a homogeneous portion of the domain. The proposed method, BIEM-FEM approach, is verified for several anti-plane (SH) and in-plane (PSV) two-dimensional cases, in which the slip is prescribed along the fault (kinematic rupture). For spontaneous rupture, we examine the performance of the BDM by computing its convergence rate for an example in a homogeneous half-space with a slip-weakening friction law on the fault. By including the boundary integral representation on the fault, without using any refinement near the crack tips, the solution converges with the same rate as problems that do not exhibit any stress concentrations. Additional two-dimensional spontaneous rupture simulations are performed for an inclined fault in a half-space for different values of the dip angle and for a folded layer system in a half-space, for both the SH and P-SV cases. Results show that the waves generated at the free surface and within the layers contribute to the propagation of the fault rupture and have a strong effect on the ensuing ground motion.



SPONTANEOUS RUPTURE MODELING OF EARTHQUAKES – TESTING THE METHODS

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Simulations of spontaneous earthquake rupture propagation and the resulting ground motion have become widely applied tools in earthquake science, mostly due to the ample computational resources that are now available. Although these computer codes can incorporate many of our ideas about how earthquakes work, the problems they solve have no analytical solutions, and so the conclusions drawn from these models about both rupture progress and predicted ground motion are difficult to validate. Our code validation group consists of more than 25 collaborators from the U.S., Mexico, Japan, and Switzerland working to test the reliability of spontaneous earthquake rupture propagation codes. We construct benchmark exercises to test different aspects of these codes. To date we have examined cases of spontaneous rupture propagation on planar vertical and dipping faults set in homogeneous and heterogeneous media. The dynamic rupture failure criterion has mostly been assumed to be slip-weakening, but we also have tested formulations of rate-state friction. We focused two of our benchmarks on testing extreme, complete stress-drop ruptures on a dipping normal fault and were able to successfully reproduce the ground motions produced by Andrews *et al.* (BSSA, 2007). In 2010 we plan two new sets of benchmarks. The first will examine non-planar fault geometry, specifically branching faults; the second will test thermal pressurization. For more information about work done to date and to join us or follow our continued progress, please contact me and also see our website, http://scecdata.usc.edu/cvws.

THEORETICAL ANALYSIS OF STATIC MODE-II CRACK IN A TWO-LAYERED MEDIUM – INTERFACIAL FAULT AND INTERSECTING FAULT

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A fault in an infinite homogeneous medium is widely assumed as a model for earthquake fault. It is, however, well known that the earth's crust is heterogeneous and its structure is approximated well by a layered medium. Hence, to understand the effect of material interface on faulting, we theoretically analyze stress field around a 2-D static mode-II crack in a two-layered elastic medium. Here we note that background stress in a layered medium should be discontinuous across the interface theoretically in order to fulfill a condition of continuity of displacement and traction across the interface.

First, we discuss an interfacial fault. Although almost all of preceding studies had focused only on stress along the interface, we analytically derive 2-D distribution of stress around the fault. With the solution, we show that contrast of ΔCFF is weaker than contrast of background stress between two media. Hence it is implied that asymmetricity of epicentral distribution of aftershocks, if any, might be due to discontinuity of background stress rather than the asymmetricity of ΔCFF.

Next, we consider a fault that intersects with the interface. In this case, stress drop is assumed as discontinuous across the interface because of discontinuity of background stress. As a result of BIEM, stress intensity around fault tip depends on an orientation of maximum principal stress (σ_1). If σ_1 is parallel or normal to the interface, stress intensity takes higher value in the stiffer medium, but if σ_1 is at 45 to 60 degree from the interface, it takes higher value in the softer one. This can explain a scenario of rupture of 2007 South African goldmine earthquake (M2) that stopped after intersecting with the interface between dyke and hostrock.

PROPERTIES OF DYNAMIC SLIP PULSES IN A 2D SLAB

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Earthquake ruptures are believed to propagate predominantly as self-healing pulses yet the dynamics of these pulses is not completely understood: what controls their rise time and rupture speed? Large earthquake ruptures (M larger than 7) necessarily behave as pulses due to healing by the waves reflected at the top and bottom of the seismogenic zone. To obtain insight on the dynamics of self-healing pulses on very long faults we studied dynamic ruptures running across the middle longitudinal plane of a 2D elastic slab of finite thickness *H*. Reflected waves from boundaries are also present in this 2D problem and pulse-like ruptures are naturally produced. We studied this model numerically, applying the spectral element method implemented in the SEM2DPACK code, assuming uniform slip-weakening. We monitored the relation between rupture properties such as final slip, peak slip rate, stress drop, rise time and rupture speed. We found a transition between sustained and dying pulses as a function of slab thickness *H*, well predicted by a critical ratio of fracture energy to potential energy. The limiting speed of sustained rupture is independent on *H* and is consistent with analytical results based on a non-classical crack tip equation of motion appropriate for this geometry. In super-shear ruptures rise time approaches the travel time of the reflected phases, but in sub-shear ruptures it decreases continuously to much shorter values due to reflected waves faster than rupture fronts. The rupture arrest transition controlled by *H* and the supershear transition controlled by background stresses are observed also in 3D ruptures on very long faults (see also Dalguer *et al.* in this workshop). We will also report on pulse properties in an elasto-plastic slab and on non-planar faults.

VALIDATION OF CHATACTERIZED SOURCE MODEL OF INTRASLAB EARTHQUAKES FOR STRONG MOTION PREDICTION

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We proposed a prototype of procedure for strong ground motion prediction of intraslab earthquakes. It is based on the characterized source model of intraslab earthquakes constructed by the slip characterization of heterogeneous source models and the relationships between SMGA and asperity. Iwata and Asano (2010) obtained the empirical relationships of rupture area (S) and total asperity area (S_a) to seismic moment as follows, with assuming power of 2/3 dependency of S and S_a on seismic moment,

$$S\ (\mathrm{km}^2) = 6.57\times10^{-11}\times M_o^{2/3}\ (\mathrm{Nm}) \qquad (1)$$
$$S_a\ (\mathrm{km}^2) = 1.04\times10^{-11}\times M_o^{2/3}\ (\mathrm{Nm}) \qquad (2)$$

Based on the empirical relationships obtained above, we proposed a procedure for constructing source models for intraslab earthquakes for strong motion prediction.

1. Give the seismic moment M_o.
2. Obtain total rupture area and total asperity area according to the empirical caling relationships between S, S_a, and M_o given by Iwata and Asano (2010).
3. Square rupture area and asperity are assumed.
4. Source mechanism is assumed to be same as that of small events in the source region.
5. Plural scenarios including variety of number of asperities and rupture starting points are prepared.

We are testing this procedure by simulating strong ground motions for several observed events such as the 2001 Geiyo earthquake (M_w 6.8, Hypocentral depth = 46 km) by the empirical Green's function method (Irikura, 1986). Effects of the scenarios on estimated ground motions are discussed. Simulated ground motions using source parameters given by the characterized source model for crustal earthquakes (Irikura and Miyake, 2001) are compared to those for intraslab earthquakes.

SYNTHETIC SOURCE SPECTRUM MODELING OF RUPTURE DIRECTIVITY WITH APPLICATION TO M < 5 PARKFIELD EARTHQUAKES

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Studies of large earthquakes have found that many events exhibit unilateral rupture. Theoretical modeling of strike-slip ruptures along a smooth, bimaterial interface suggests that such ruptures will have a preferred rupture direction and will produce asymmetric ground motion. Whether or not this model explains the predominance of unilateral rupture in large earthquakes remains to be determined, and could have important implications for earthquake source physics studies as well as for seismic hazard estimates. We analyze source spectra of small earthquakes ($M < 5$) from the Parkfield region to look for evidence of unilateral rupture directivity along the San Andreas Fault. The planar location of seismicity in this region and the separation of two distinct crustal blocks by the fault produce a test case for determining whether or not a preferred rupture direction exists. We quantify the differences in the spectra based on the azimuth between the sources and stations to detect possible directivity of each event. We model synthetic spectra for assorted distributions of seismicity by modifying a Brunetype source spectrum with a Doppler shift of frequency, and then statistically compare these synthetic populations with our measured results. Our results do not show a strong indication of unilateral rupture directivity in any particular direction, although our method does not currently account for vertical components of rupture directivity.

TOWARDS INFERRING EARTHQUAKE PATTERNS FROM GEODETIC OBSERVATIONS OF INTERSEISMIC COUPLING

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Ultimately, seismotectonic studies seek to provide ways of assessing the timing, magnitude and spatial extent of future earthquakes. Ample observations document the spatial variability in interseismic coupling, defined as a degree of locking of a fault during the period of stress build-up between seismic events: fully or nearly locked fault patches are often surrounded by aseismically creeping areas. However, it is unclear how these observations could help assess future earthquakes. Here we simulate spontaneous seismic and aseismic fault slip with a fully dynamic numerical model. Our simulations establish the dependence of earthquake rupture patterns and interseismic coupling on spatial variations of fault friction. We consider the long-term evolution of slip on a model fault where two seismogenic, locked segments are separated by an aseismically slipping patch where rupture is impeded. We find that the probability for a large earthquake to break through the rupture-impeding patch is correlated with the interseismic coupling averaged over this patch. In addition, the probability that an earthquake breaks through the rupture-impeding patch and interseismic coupling are both related to fault friction properties through a single non-dimensional parameter. Our study opens the possibility of predicting seismic rupture patterns that a fault system can produce on the basis of observations of its interseismic coupling, and suggests that regions of low interseismic coupling may reveal permanent barriers to large earthquakes.

ACCURATE AND STABLE TREATMENT OF NONLINEAR FAULT BOUNDARY CONDITIONS WITH HIGHER-ORDER FINITE DIFFERENCE METHODS

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High-order numerical methods are ideally suited for earthquake problems since they require fewer grid points to achieve the same solution accuracy as low-order methods. Though straightforward to apply these methods in the interior of a domain, it can be challenging to maintain stability and accuracy near boundaries and faults. Despite several efforts to develop high order fault boundary treatment, no codes have demonstrated greater than second-order accuracy for dynamic rupture problems, even on rate-and-state friction problems with smooth solutions.

In this work summation-by-parts (SBP) finite difference methods are used with a simultaneous approximation term (SAT) to achieve a stable high-order method for dynamic ruptures with rate-and-state friction. SBP methods use centered spatial differences in the interior and one-sided differences near the boundary. The transition to one-sided differences is done in a manner that permits one to provably maintain stability as well as high order accuracy. In many methods the boundary conditions are strongly enforced by modifying the difference operator at the boundary so that the solution there exactly satisfies the boundary condition. This approach often results in instability when combined with high-order difference schemes. In contrast, the SAT method enforces the boundary conditions in a weak manner by adding a penalty term to the spatial discretization.

Tests of spontaneous rupture propagation on strongly velocity-weakening rate-and-state faults demonstrate the theoretical accuracy and stability of the method. The methods can be extended, through the use of coordinate transformations, to explicitly account for fault roughness and free-surface topography, both of which may be key to realistic ground motion prediction.

REPRODUCING SOURCE CHARACTERISTICS OF THE 1999 CHI-CHI EARTHQUAKE IN A MODEL WITH LABORATORY-BASED FAULT PROPERTIES

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The 1999 Chi-Chi earthquake is one of the best-studied earthquakes. One interesting observation is the difference in slip and high-frequency content of the strong motion in the Northern and Southern regions of the earthquake source. The Northern region had larger slip but lower high-frequency content than the Southern region, which contained the earthquake epicenter.

We create a scenario similar to the Chi-Chi earthquake in a fault model governed by Dieterich-Ruina rate-and-state friction, with temperature and pore pressure evolution due to shear heating. Our methodology allows for simulations of long-term slip in such models while accounting for inertial effects during seismic events, slow tectonic loading, and diffusion of heat and pore pressure normal to the fault (Noda and Lapusta, AGU, 2009). The fault has two regions: one with velocity-weakening steady-state friction and higher permeability (the Southern region) and the other one with velocity-strengthening (VS) steady-state friction and lower permeability (the Northern region). The fault properties used in the model are motivated by laboratory measurements on rock samples taken from boreholes on the Chelungpu fault that hosted the earthquake (Tanikawa and Shimamoto, JGR, 2009).

In the model, earthquakes always nucleate in the Southern region, as occurred in the Chi-Chi earthquake. When earthquakes enter the Northern region, lower permeability there activates dynamic weakening due to pore pressurization, and the Northern region ends up having larger slip in such model-spanning events. At the same time, VS friction in the Northern region reduces the high-frequency content of the rupture tip. Hence the Northern region has higher slip but lower high-frequency radiation, as indicated by observations.

CONSTRUCTION OF AN EFFECTIVE FRICTION LAW EQUIVALENT TO SMALL SCALE FAULT HETEROGENEITY BY STUDYING INITIATION OF DYNAMIC RUPTURES

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Direct observation of emerged fault surface as well as results of inversions show that heterogeneity on fault is present at all scales. This leads us to investigate the feasibility of including the effects of heterogeneities smaller than the grid step size in dynamics rupture simulations .

Using a finite element code (Ma and Liu 2006), we perform 3D dynamic rupture simulations in which we impose linear slip-weakening friction law on the fault plane. A multi-scale heterogeneity is introduced by the mean of an inhomogeneous spatial distribution of the static threshold. We are able to construct an effective friction law which accounts for the smallest scale of heterogeneity. To do so, we rely on the spectral description of the initiation phase in 3D developed by Favreau *et al.* (2002) : at the beginning of the rupture, the slip growth is characterized by an eigenvalue determined by both the geometry of the heterogeneity and the slope of the friction law. Thus if the smallest scale of heterogeneity is removed and replaced by a modification of the friction law, we can conserve the eigenvalue and obtain a similar behaviour to the one of the fault with the complete heterogeneity. More precisely we find same initiations times and identical slipping patterns.

This method permits to reproduce the physical effects of small scale heterogeneity in dynamic rupture simulations without reducing the grid step. It is therefore very cost effective. Finally, this work constitutes a first step towards the understanding of the scale dependence of friction parameters, bridging the gap between laboratory and seismic measurements.

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OBSERVATION OF SLIPPING SURFACE AND EMITTED WAVES DURING SLIPPING EVENTS IN HYDROGELS FRICTION EXPERIMENTS

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We developed a friction experiment coupled to an original imagery technique which permits to have a sight both at the frictional interface and at the waves emitted in the bulk during a slip event. We use soft solids sliders, namely hydrogels of PVA, in contact with either glass or sandpaper. The huge interest of such soft solids is that their shear wave velocity is orders of magnitude smaller than their sound velocity. Ultrasonic waves can thus be used to probe all phenomena occurring at velocities close to shear wave velocity, that is, typically, rupture nucleation and propagation, as well as shear waves themselves.

The imagery setup, developed in the field of elastography (Sandrin *et al.*, 2002) consists of a line of 64 ultrasonic emitter-receptors which can emit pulses and receive echo at rates up to 5000 Hz. Spatial correlations between each successive echo permits to determine the displacement that occurred between two pulses, thus the local instantaneous particle velocity. A first application of this setup would be to visualize the nucleation of slipping events and investigate their modes of propagation, like self-healing pulses or supershear propagation. It permits also to have an insight at the millimetric level of the phenomena which control the macroscopic stick-slip behaviour of the slider, and study their dependency with the driving velocity. This technique is thus very promising for shedding some welcome light on rupture physics.

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THE EFFECTS OF FAULT STEPOVERS ON GROUND MOTION

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Using 3D dynamic models, we investigate the effect of fault stepovers on near-source ground motion. We use the 3D finite element method to model the dynamic rupture, slip, and ground motion of two parallel strike-slip faults with an unlinked overlapping stepover of variable width. We modeled this system as both an extensional and a compressional stepover, and compared the results to those of single planar faults. We also compared these models to the ground motion from a planar faults of the same length. We found that the presence of a stepover along the fault trace reduces the maximum ground motion when compared to a long planar fault. Whether the compressional or extensional stepover exhibits higher ground motion overall depends on the width of the separation between the faults. We also found that there is a region of reduced ground motion at the end of the first fault segment when the faults are embedded in a homogeneous material. We experiment with embedding these faults in various materials with properties corresponding to real-world rocks. We also experiment with placing realistic material interfaces along the faults, such as a sedimentary basin in an extensional stepover, a layer of sedimentary rock over a granitic basement, and a damage zone around the entire fault. These configurations alter the pattern of ground motion in a more complex manner than merely scaling the intensity of the motion up or down depending on the material properties. The distribution of slip rate at depth and the shape of the rupture front, which are affected by the material interfaces and properties, in turn affect the distribution of motion on the surface. The results may have implications for ground motion prediction in future earthquakes on geometrically complex faults.

SOURCE INVERSION VALIDATION: QUANTIFYING UNCERTAINTIES IN EARTHQUAKE SOURCE INVERSIONS

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Earthquake source inversions image the rupture evolution on faults using seismic and/or geodetic data, and represent important research tools in seismology that reveal the complexity of rupture processes. Researchers use source-inversion results to study earthquake mechanics, to develop dynamic rupture models, to build tools for generating rupture realizations for ground-motion simulations, and to perform Coulomb-stress modeling. In these applications, the underlying imaged rupture models are treated as “data”, but the uncertainties in these data (i.e. source models obtained from solving an inherently ill-posed inverse problem) are hardly known, and almost always neglected.

The Source Inversion Validation (SIV) project is born out of recent efforts to better understand the intra-event variability of earthquake rupture models, evident in the finite-source rupture model database. The SIV project cooperates with CSEP, the Collaboratory for the Study of Earthquake Predictability, and employs design concepts and software codes from CSEP earthquake forecast testing centers. Following the initial SPICE source inversion blind-test, we have conducted several workshops to set up a longstanding and rigorous testing platform to examine the current state-of-the-art in earthquake source inversion and to develop robust approaches to quantify uncertainties in inverted rupture models.

In this talk we review the current status of the SIV project and the findings and conclusions of the recent workshops. We briefly discuss various source-inversion methods, how they treat uncertainties in data, and assess the posterior model uncertainty. We also examine the basic issue of computing accurate/correct Green’s functions, and present the strategy of the SIV-project for the coming years.

DESIGNING A NETWORK OF SEISMIC ANTENNAS FOR SOURCE IMAGING

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The critical information needed to discriminate among physical models of earthquake dynamics is contained in small scales associated to the high frequency wave field. Incomplete knowledge of crustal heterogeneities limits the resolution of current source imaging techniques to length scales of several kilometers. Recordings from small scale arrays of seismometers can be processed to determine the direction of arrival (DOA) of high-frequency waves and track the complex evolution of the rupture front. We are investigating how a highly clustered strong motion network composed of multiple small aperture arrays can allow robust on-parametric source imaging of large earthquakes. A global, permanent deployment operation can be costly and complicated. Alternatively the arrays can be deployed at pre-selected sites immediately after a large M > 7.5 earthquake to record M > 6 aftershocks with unprecedentedly high resolution. From the CMT catalog, estimates of the chance of success are over 35% if the deployment is done within 12 hours after the mainshock. Locating the arrays close to the fault improves source location but also decreases the field of view. We find the optimal fault-array distance to be of order 5 km and that a multi-array network with complete coverage requires a spacing of order 20 km between arrays .We also experiment the concept of designing arrays with frequency invariant beam patterns. A example of the geometry optimization of a branch-style 2d array is demonstrated. We explored a DOA estimator based on the multitaper cross power spectrum and the Incoherent MUSIC method to circumvent specific difficulties: wideband, non-stationarity and scattering. The multitaper-IMUSIC method achieves a much sharper DOA estimation than the conventional beamforming.

SOURCE PROPERTIES OF THE JANUARY 2010 M7 HAITI EARTHQUAKE ESTIMATED BY BACK PROJECTION OF WAVES RECORDED BY THE NATIONAL SEISMIC NETWORK OF VENEZUELA AND THE USARRAY

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Back projection of teleseismic waves based on array processing has become a popular technique for earthquake source inversion. By tracking the moving source of high frequency waves, areas of the rupture front radiating the strongest energies can be imaged. The technique has been previously applied to track the rupture process of the Sumatra earthquake and the supershear rupture of the Kunlun earthquakes. The challenge with the 2010 M7.0 Haiti earthquake is its very compact source region, possibly shorter than 30 km. Preliminary results from back projection using US-Array or the European network reveal little detail about the rupture process. In this study, we made an effort towards imaging the Haiti earthquake using multiple seismic array networks, including the USArray and the National Seismic Network of Venezuela run by FUNVISIS. The FUNVISIS network is composed of 22 broad-band stations with an East-West oriented geometry, and is located approximately 10 degrees away from Haiti in the perpendicular direction to the Enriquillo fault strike. This is the first opportunity to exploit the privileged position of the FUNVISIS network to study large earthquake ruptures in the Caribbean. We applied back projection methods based on traditional stacking and signal subspace techniques, and we incorporated Green's function deconvolution in the array processing. The preliminary result is encouraging: we observe an east to west rupture propagation along the fault, consistent with a compact source and rupture propagation at subshear speed. These efforts could lead the FUNVISIS seismic network data to play a prominent role in the timely characterization of the rupture process of large earthquakes in the Caribbean, including the future ruptures along the yet unbroken segments.

VALIDATION AND APPLICATION OF FEM AND FDM SIMULATION CODES FOR DYNAMIC EARTHQUAKE RUPTURE

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We have developed three-dimensional simulation codes of dynamic earthquake rupture with the finite element method and the finite difference method. The FEM code with a voxel mesh is formulated by Koketsu *et al.* (2004), an unstructured FEM code is newly developed in this study, and the FDM code is based on displacement formulation by Kase and Kuge (2001). Fault planes are represented by split nodes in the three codes, therefore the thickness of the fault zone is assumed to be zero. In the two FEM codes, stress on the fault is formulated as equivalent nodal forces. We applied all the codes to the benchmark tests of spontaneous strike-slip faulting used in the SCEC/USGS dynamic earthquake rupture code verification (Harris *et al.*, 2009), and our examples of spontaneous dip-slip faulting as well. We then assess the accuracy of the numerical methods for dynamic earthquake rupture simulations with the voxel FEM, the unstructured FEM that introduces arbitrary shape of fault plane, and the FDM codes. The two FEM codes provided similar solutions to that of the FDM code, but they provided slightly faster rupture propagation.

The unstructured FEM code has an advantage to easily handle fault geometry and heterogeneous material properties. We applied the code to the M_w 7.6 1978 Miyagi-oki, Japan, earthquake to examine geometric effects of the Pacific plate. We compare spontaneous dynamic rupture models of the FDM simulation on a planar fault by Kimura *et al.* (2010) with the unstructured FEM simulation on a curved fault. In this Miyagi-oki earthquake case, the geometric effects seem not to be significant due to the smoothness of the plate boundary.

THE TSN MODELING OF RUPTURE PROPAGATION WITH TWO SLIP-DEPENDENT FRICTION LAWS

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We present an adaptive smoothing algorithm for reducing spurious high-frequency oscillations of the slip-rate time histories in the finite-element—traction-at-split-node modeling of dynamic rupture propagation on planar faults with the linear slip-weakening and Ohnaka-Yamashita friction laws. The algorithm spatially smoothes the trial traction on the fault plane. The smoothed value of the trial traction at a grid point and time level is calculated if the slip is larger than 0 simultaneously at the grid point and 8 neighboring grid points on the fault. The smoothed value is a weighted average of the Gaussian-filtered and unfiltered values. The weighting coefficients vary with slip.

Numerical tests for different rupture propagation conditions demonstrate that the adaptive smoothing algorithm effectively reduces spurious high-frequency oscillations of the slip-rate time histories without affecting rupture time. The algorithm does not need an artificial damping term in the equation of motion. We implemented the algorithm in the finite-element part of the 3D hybrid FE-FD method. This makes it possible to efficiently simulate dynamic rupture propagation inside a finite-element sub-domain surrounded by the finite-difference sub-domain covering a major part of the whole computational domain.

If the spurious high-frequency oscillations of the slip rate do not change development of the rupture, smoother slip-rate time histories can be also obtained by a posteriori filtration. We present new approaches utilizing empirical mode decomposition and discrete wavelets, and compare them with the traditional low-pass filtration.

We also present results of numerical investigations of the effect of the spatial sampling on the accuracy and smoothness of the simulated slip rates.

A COMPARATIVE STUDY FOR NUMERICAL RUPTURE SIMULATION WITH WAVE PROPAGATION COUPLING

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Despite some possibilities to carry laboratory rupture experiments, the need to quantify the effects of various fault parameters made Numerical modeling approaches essential for understanding dynamic rupture and its interaction with the generated wave propagation. As in mechanical engineering, the fault is materialized by the contact of two surfaces. Finite elements Methods are adapted for modeling a geometrical fault. To model rupture in regions with large deformation we implement a Lagrangian formulation. Contact constraints are enforced by a Lagrange Multiplier approach. A 3D implementation of contact algorithms is challenging but is necessary for the understanding of earthquake processes, as well as the modelization of 3D asperities at small scales.

In the view of setting a full 3D model, we present 2D numerical simulations for both supershear and sub-shear speed rupture cases implemented with Plast2D. Plast2D (under GPL) is developed by L. BAILLET at the LGIT Grenoble and enables 2D simulations of various frictional behavior at the fault. We show comparative studies with the split-to-node technique used by most implementations of 2D benchmarks from the SCEC/USGS Spontaneous Rupture Code Verification Project.

3D SIMULATIONS OF LONG-TERM FAULT SLIP WITH DYNAMIC WEAKENING: RELATION BETWEEN LOCKED PATCHES AND EARTHQUAKE-INDUCED STRESS CHANGES

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Dramatic weakening during coseismic fault slip would make a large difference in the dynamics of earthquake sequences, for example, by allowing low long-term heat generation rate and interseismic shear stress on a fault (e.g., Lapusta and Rice, 2003) and promoting pulse-like type of rupture propagation (e.g., Perrin *et al.*, 1995; Noda *et al.*, 2009). We have developed a suitable methodology to implement hydro-thermal effects due to coseismic frictional heating (Noda and Lapusta, AGU, 2009). Our model accounts for coseismic inertial effects as well as slow tectonic loading on a fault.

Here we focus on the distribution of stress change (or local stress drop) in an earthquake event and its relation to the location of locked patches. Interseismically, creeping motion penetrates into a velocity-weakening (VW), potentially seismogenic zone. An earthquake occurs when the creeping part of the VW zone is large enough to nucleate unstable slip. We observe that the stress drop in our simulations is larger in these creeping parts of the seismogenic zone than in the completely locked patches, since the creeping areas reach high static strength before the event, while the locked parts of the fault have relatively low prestress. The stress drop can even be negative locally within a locked patch (See Figure).

Regions of negative stress drop surrounded by positive stress drop have been observed (e.g., Bouchon 1997). One possibility is that such regions are velocity-strengthening areas. Our results suggest a potential alternative interpretation. In particular, in our models, regions of smaller or negative stress drop can have quite healthy slips that are larger than the average slip in the event.

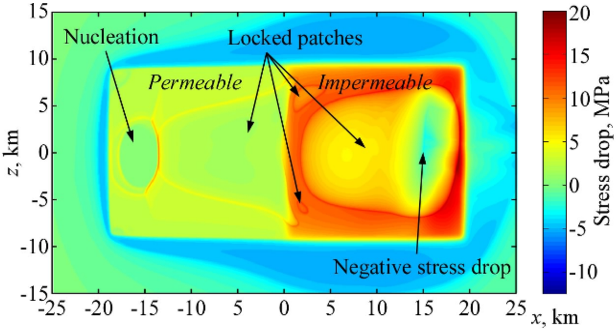

Figure. Stress drop distribution in one of the earthquakes in a sequence. This event ruptures two patches of different hydraulic diffusivities.

LABORATORY AND NUMERICAL MODELS OF THRUST FAULTS

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It is well known that the rupture, slip, and ground motion patterns of dip-slip faults can be quite different from those of otherwise-equivalent strike-slip faults. The primary reason is the asymmetric geometry where the fault meets the free surface. Numerical models and some observations imply that thrust faults should experience significantly larger motion on the hanging wall than on the footwall, and that this asymmetry is produced by a strong breakout phase from the free surface that propagates back down along the fault and through the surrounding medium. To test these and other predictions, we perform experimental thrust faulting models using homalite in a laboratory setting. The experimental procedure allows for the accurate measurement of particle velocity time histories as well as observations of rupture propagation. The experimental results indeed display asymmetric particle motion between the hanging wall and footwall, among other features. We attempt to fit these experimental models with 2-D and 3-D dynamic finite element models, and find that some of the complexity in the laboratory model particle time histories may be explained by 3D effects associated with the homalite sample's finite width, including wave reflections off the edges of the homalite material sample. We will discuss which of the experimental results are applicable to real earthquakes.

DYNAMIC RUPTURE MODELING ON UNSTRUCTURED MESHES USING A DISCONTINUOUS GALERKIN METHOD

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The simulation of earthquake rupture dynamics and seismic wave propagation using a discontinuous Galerkin (DG) method was recently presented by J. de la Puente (2009). A considerable feature of this study regarding spontaneous rupture problems was the combination of the Arbitrary highorder DERivatives (ADER) approach to provide high accuracy in space and time with the discretization on unstructured meshes. In a velocity-stress formulation of a DG scheme variables are naturally discontinuous at the interfaces between elements. The so-called Riemann problem can then be solved to obtain well defined values of the variables at the discontinuity itself. This is in particular valid for the fault at which a certain friction law has to be evaluated. Hence, the fault is honored by the computational mesh. This way, complex fault geometries can be modeled adequately with small elements while fast mesh coarsening is possible with increasing distance from the fault. A further advantage of the scheme is that it avoids spurious high-frequency contributions in the slip rate spectra. Due to the strict locality of the scheme, as only direct neighbors communicate, excellent parallel behavior can be observed. In order to test the accuracy of the method a 2D version of the Southern California Earthquake Center benchmark for spontaneous rupture simulations was employed. We will present recent developments concerning ADER-DG methods on unstructured meshes coupled with dynamic rupture problems. Investigations in complex non-planar faults in an acceptable expenditure of time together with high accuracy are feasible now.

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LOCATING A SMALL CHANGE IN A MULTIPLE SCATTERING ENVIRONMENT

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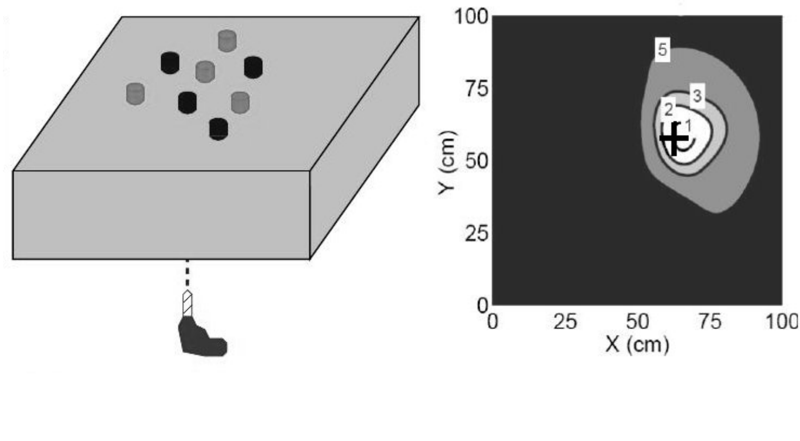
We present an imaging technique to locate a weak perturbation in a multiple scattering environment. We derive a formula to predict the spatio-temporal decorrelation of diffuse coda waves induced by an extra-scatterer. Locating this new defect is then formulated as an inverse problem which is solved by a maximum likelihood approach. Using elastic waves in the 100-350 KHz frequency band, we show that the position of a millimetric hole drilled in a heterogeneous concrete sample can be retrieved with a precision of a few cm. We illustrate the robustness of the method and define an optimal time of propagation that depends on the geometry of the acquisition and the diffusion constant of the medium. Potential application to seismic coda waves includes volcano monitoring and eruption prediction.



REVEALING SOURCE AND PATH SENSITIVITIES OF BASIN GUIDED WAVES BY TIME-REVERSED SIMULATIONS

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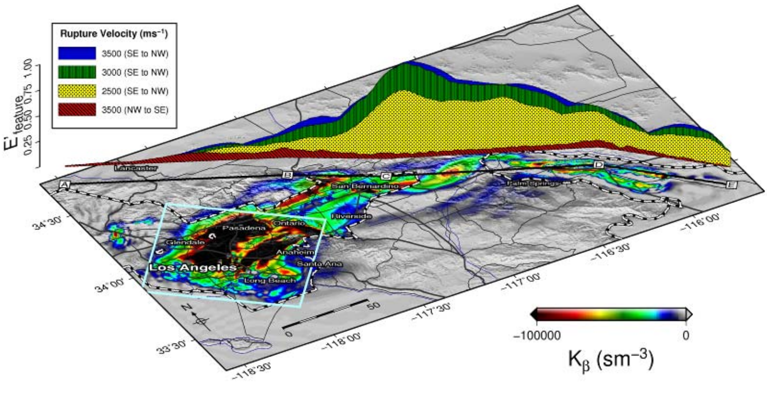
Simulations of earthquake rupture on the southern San Andreas fault (SAF) predict large excitation in the San Gabriel/Los Angeles (SGB/LAB) and Ventura (VTB) basins, with amplitudes strongly depending upon source details (slip distribution, direction and rupture velocity). We propose a method for rapid calculation of the sensitivity of such wavefield features (i.e. excitation in the SGB/LAB) to perturbations of the source kinematics and to details of the velocity structure. The method is based on isolating the wavefield feature of interest and calculating its pullback onto the source by means of a single time-reversed (adjoint) simulation. This allows calculation of the feature excitation resulting from any source perturbation without running a forward simulation. We find that excitation in the SGB/LAB is greatest for rupture concentrated between the northern Coachella Valley and the Transverse Ranges and propagating to the NE, while excitation in the VTB is mostly sensitive to rupture on the northern segment of the SAF. Basin amplitudes are higher for super-shear rupture velocities than for sub-Rayleigh velocities along these segments. The same time-reversed calculations also yield path-sensitivity kernels which reveal how the energy is propagating from the source (SAF) to the densely populated areas of the SGB/LAB and VTB, similar to Fréchet kernels used in seismic tomography. These pathsensitivity kernels confirm our earlier interpretation that the excitation in the SGB/LAB and VTB is caused by long-range channeling along sedimentary waveguides. SAF segments directly connected to waveguides produce the largest excitation in the basins, adding to our understanding of the complicated interaction between source, path and site effects.



DYNAMIC MODELS OF FAULT STEPOVERS WITH RATE-STATE FRICTION

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We use a two-dimensional dynamic finite element method to explore the effects of friction parameterization on the dynamics of fault systems with stepovers. In particular, we investigate how rate-state friction affects the process by which rupture may jump across the stepover. We find that for the dilational fault stepover case, the maximum stepover width rupture can jump from one fault segment to the next is greater than the compressional fault stepover case by a factor of 3/2. In addition, rupture along the secondary fault segment is always accompanied by a decrease in normal stress in the cases of both the extensional and compressional stepover. Rupture along the secondary fault segment for the compressional fault stepover case reaches super-shear velocity at a minimum stepover width. We compare our results with standard rate-state friction, with a strong rate-weakening parameterization, and with slip-weakening friction.

WHAT DID WE LEARN FROM THE SPICE EARTHQUAKE SOURCE INVERSION BLINDTEST I?

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We participated in the BlindTest I exercise of the SPICE Earthquake Source Inversion Validation project by inverting the rupture process of a pseudo source using synthetic seismic waveforms at a near-fault strong motion network. Nine groups had previously participated in this excise, but “4 out of 9 inversion results are, statistically speaking, not better than a random model with somehow correlated slip!” (Mai *et al.*, 2007). Here we simultaneously invert the slips and the shapes of the asymmetric cosine slip rate function of 560 1 km by 1 km subfaults by matching broadband velocity waveforms within period from DC to 2 Hz, using our finite fault method which carries waveform inversions in wavelet domain (Ji *et al.*, 2003). The effects of subfault size and data noise have also been explored. Our investigations result in mixed conclusions. On one hand, our study demonstrates that for the BlindTest I problem, the finite fault source inversion is robust, even with large incoherent perturbations. With precise velocity structure, precise fault geometry, and good station coverage, the fault slip is reasonably well retrieved even using the data including additional 35% Gaussian noise. On the other hand, coherent perturbations, such as those due to model parameterizations and bandpass filter to the data, have clear impacts to the inverted results, despite the small effects to the value of misfit function. In particular, using band-limited seismic data could lead to erroneous results even if the synthetics have an excellent fit to the data. Finally, the uncertainty of source inversion is also affected by the geometric extension of the fault. For a vertical strike-slip earthquake, the along strike slip variations are better constrained than the variations in down-dip direction.

SLIP AT THE SURFACE AND AT DEPTH IN LARGE EARTHQUAKES

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In large earthquakes, slip generally breaks the surface, and can be measured directly. This provides a unique view of the earthquake source, with spatially-dependent model-independent information. Pursuing this valuable information, we present new ways of quantifying the observed slip for a suite of large earthquakes. To make connections with what is happening at depth, we explore a three dimensional scalar elastodynamic model with a range of frictional properties on the fault. We examine the situation of a seismogenic layer with uniform frictional properties surrounded below and above by a stable sliding layer with a different set of uniform properties. The model is run for a long time, generating complex sequences of ruptures which leave irregular stresses as initial conditions for subsequent ruptures. We examine how slip in large events varies along-strike and with depth, as a variety of frictional properties of the stable sliding layers are changed. Results show a remarkable insensitivity of surface slip behavior to dramatic changes at depth.

BENCHMARKING PYLITH FOR 2-D AND 3-D DYNAMIC SPONTANEOUS RUPTURE MODELING

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PyLith is an open-source, community finite-element code for quasi-static and dynamic tectonic deformation problems. Dynamic fault interface conditions have been implemented in the latest release of PyLith (version 1.5.0) to enable modeling of earthquake processes via fault constitutive models, including slow quasi-static and fast dynamic slip; previous versions of PyLith were limited to kinematic ruptures. Solving the fault constitutive equations using a Schartz preconditioner resulted in much faster convergence than using a Jacobi preconditioner. We have implemented various fault constitutive models in PyLith, including slip-weakening and rate-and-state friction. We tested these new features using four SCEC benchmarks (1) slip-weakening friction for a vertical strike-slip fault (2) rate- and state-friction for a vertical strike-slip fault (3) slip-weakening for a dipping fault with dip-slip motion, and (4) slip-weakening for a dipping fault with dip-slip motion and Drucker-Prager plasticity. We report on comparisons of our results for these benchmarks, using different cell types. We have also simulated dynamic rupture in branched fault systems and compare our results to published simulations of subduction earthquakes that trigger slip on secondary splay faults, a process relevant to tsunami hazard. Our eventual goal is to create a methodology, based on PyLith, that would be able to simulate the long deformation histories of a fault, including quasi-static and dynamic phases, in realistic bulk rheologies.

EARTHQUAKE SOURCE STATISTICS INFERRED FROM EARTHQUAKE SOURCE PHYSICS

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It is an essential element to understand the underlying physics of earthquake rupture processes for a better understanding of near-fault ground motion characteristics. But it is also important to quantify the variability of possible rupture scenarios in a systematic way for accurate prediction of the ground motion intensity and variability (median and sigma). I propose to use one point and two point statistics of key kinematic source parameters to quantify the variability of fault-fault earthquake source models, such as final slip, rupture velocity, and slip duration. The heterogeneity of the source parameters and their linear dependency (coupling) are characterized by two point statistics, i.e., auto- and cross-coherence. One point statistics, i.e., the probability density function (PDF) for each source parameter at a given point, can also characterize many important features of earthquake rupture dynamics, such as subshear or supershear rupture, crack- or pulse-like rupture, stick-slip or creep. The strength of this approach is that all these features can be handled systematically in the form of a single multi-variate probability density function. The author will cover how to extract main statistical features of the source parameters from both dynamic and kinematic rupture models and reproduce them in finite-fault source modeling for ground motion simulation. Now we are heading toward extended earthquake rupture forecast (eERF) for seismic hazard analysis with full waveform modeling.

SCALING OF EARTHQUAKE RUPTURE GROWTH IN THE PARKFIELD AREA: SELF-SIMILAR GROWTH AND SUPPRESSION BY THE FINITE SEISMOGENIC LAYER

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We propose a new framework on the scaling of earthquake rupture growth time history, and scale the moment rate and the cumulative moment functions of earthquakes over a wide magnitude range (M_w 1.7 – 6.0) in Parkfield, California. The moment rate and the cumulative moment functions of the small and medium earthquakes (M_w 1.7 – 4.6) are derived by slip inversion analyses with the empirical Green's function technique. The moment rate functions of the investigated earthquakes, except the Mw 6.0 event, are similar to each other, increasing rapidly in the first half (growth stage) and decelerating in the latter half (decline stage). In the growth stage, the cumulative moment functions are approximated by $M_o(t)[\mathrm{Nm}] = 2 \times 10^{17}(t[\mathrm{s}])^3$ independent of the final size of the earthquakes. The proportionality of the cumulative moment to the cube of time implies self-similarity during earthquake rupture growth. In decline stage, the cumulative moment function veers off the common rupture curve. The M_w 6.0 event also grows along the same rupture curve until 1 s, after which the cumulative moment function is proportional to time from the onset itself. This is because the finite seismogenic layer limits the vertical extent of dynamic rupture. Our method and result contribute to our understanding of earthquake source physics, especially on earthquake rupture growth processes, which may help to improve earthquake early warning techniques.

SPONTANEOUS DYNAMIC RUPTURE PROPAGATION BEYOND FAULT DISCONTINUITIES: EFFECT OF THERMAL PRESSURIZATION

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We investigate dynamic rupture propagation beyond fault discontinuities, on the basis of 3-D numerical simulations for spontaneous dynamic ruptures including thermal pressurization (TP).

A range of several isolated fault segments often sequentially ruptures during an earthquake. In previous numerical simulations on dry fault systems, rupture sometimes fails to propagate to an unconnected fault, and the rupture, which succeeds to propagate, is usually triggered near the Earth's surface. These features of simulated rupture disagree with those of real earthquakes. To overcome the gaps between the simulations and real earthquakes, we test effect of TP on spontaneous dynamic rupture processes on two vertical strike-slip fault segments. The numerical algorithm is based on the finite-difference method by Kase and Kuge (2001). On faults with TP, we allow effective normal stress to vary with pore pressure change by the formulation of Bizzarri and Cocco (2006).

We reveal that rupture can jump wider stepovers due to TP and that TP on a primary (nucleating) fault enables rupture to jump at deep portions, which can explain the gaps between the previous numerical simulations and real earthquakes, without introducing the heterogeneity of initial stress and/or friction. Our numerical simulations under depth-dependent stress further suggest that TP allows rupture to jump much wider stepovers at deep portions because it works more effectively with increasing depth. If TP works on faults, hydraulic diffusivity along with fault geometry can strongly control characteristics of rupture propagation at fault discontinuities. Our results imply that TP can have a significant role on rupture processes on real earthquakes.

OFF-FAULT YIELDING DURING DYNAMIC RUPTURES: DISTRIBUTION AND ORIENTATION

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We use 2D spectral element code to simulate dynamic ruptures on a fault governed by slip- and velocity-weakening friction with off-fault yielding and possible elastic contrast across the fault. The off-fault yielding is implemented with Mohr-Coulomb plasticity, and a continuum brittle damage that accounts for dynamic changes of elastic properties in the yielding zones (Lyakhovsky *et al.*, 1997). The studies attempt to clarify properties of dynamic ruptures and generated yielding zones for different off-fault rheologies, frictional laws, orientations of the maximum regional compressive stress relative to fault Ψ, values of the seismic *S* ratio and conditions representing different depth sections. In the current simulations, the damage rheology is used with parameters that prevent off-fault instabilities, leading to results that are generally similar to those obtained with plasticity. The location and extent of the yielding zone are found to depend on Ψ and the crack vs. pulse mode of rupture in agreement with previous studies. The off-fault yielding zone is wide for conditions representing shallow depth and becomes progressively localized for conditions representing deeper section. The intensity of plasticity/damage for both rupture modes is enhanced for larger regional stress, but the width can be suppressed due to higher confining pressure and larger cohesion. The angle Φ representing expected microcrack orientations is shallow on the compressional side and steep on he extensional side. For Ψ = 45°, the yielding occurs on the extensional side and Φ increases with decreasing *S* ratio. A velocity contrast across the fault produces steeper angles on the compliant side compared to the stiffer side for situations representing the same quadrant.

COMPLEX BEHAVIOR AND SCALING RELATIONS IN SLIDING FRICTION OF POLYMER GELS

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Laboratory experiments have been conducted for years to understand underlying mechanisms of rupture dynamics along faults [1]. Most of such studies are aimed at model experiments for elementary processes, while very few are designed to study the rupture dynamics in a wide area, where spatio-temporal complexity and the interactions between the faults are important.

In this presentation, we report our experimental studies on spatio-temporally heterogeneous stick-slip motions in the sliding friction of a poly-methyl methacrylate (PMMA) block sliding on a soft poly-dimethyl siloxane (PDMS) gel plate (see Figure 1). The probability distributions for the drop in frictional force obeys a power law, similar to Gutenberg-Richter's law for earthquakes, and the exponent of the power law decreases with increasing plate velocity. Bimodal distributions of the force at initiation of the events is also observed, suggesting that there are two types regimes, i.e., small event regime and quiet regime prior to large events during loading period. We propose a simple model to explain the plate velocity dependence on the power law exponent, which agrees well with experimental results. Furthermore, the relationship between the event size and its duration are shown. We find that the scaling relation $T \sim \delta F^{\alpha}$ with the exponent α satisfies 1; 1/3 [2] as well as 1/2, which implies a new class of rupture behavior.

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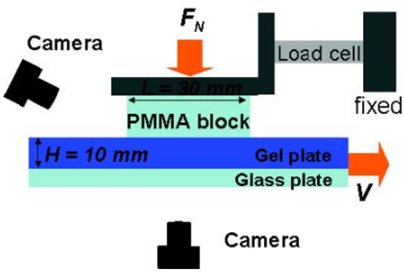

CO- AND POST-SEISMIC KINEMATIC MODEL FOR THE APRIL 6 2009 MW 6.3 L'AQUILA EARTHQUAKE BY INVERSION OF THE STRONG MOTION, GPS, AND INSAR DATA

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M_w 6.3 L'Aquila earthquake is the best-recorded normal-faulting event in near-source strong motion observations. 17 strong motion accelerographs are within 50 km of the surface projection of the fault plane. Of these 10 are within 20 km, and 4 are above the fault plane. In addition to the strong motion observations there are static measurements including GPS and InSAR. Having both seismic and static recordings provides excellent coverage of faulting for the mainshock and aftershocks.

We use strong motion records and static field measurements to invert simultaneously for two models: a co-seismic kinematic model and a postseismic slip distribution. We introduced this approach because the static field records include deformation that occurred several days following the mainshock. The co-seismic model describes the rupture process, which can explain both seismic and static data. The post-seismic model shows the slip on the fault that cannot be explained by the seismic data.

The fault has a dip of 55 degrees to the southwest constrained by the aftershock hypocenter locations given by Chiaraluce at INGV. In our coseismic model, the rupture initiates at a depth of 9.2 km and then primarily propagates updip and to southeast for over 20 km with an average velocity of 2.0 km/s along strike and about 2.0 km/s updip. The maximum slip is about 80 cm in two locations, one near the hypocenter and the other about 6-8 km southeast of hypocenter. The co-seismic moment is 3.2×10^{18} Nm. In our post-seismic model, 40 cm slip appears above the hypocenter and 20 cm slip around the hypocenter. The post-seismic model has a moment of 7.8×10^{17} Nm.

We will present this approach that inverts for co-seismic and post-seismic model based on all of the data.

SLIP ACCELERATION GENERATES SEISMIC TREMOR LIKE SIGNALS IN FRICTION EXPERIMENTS

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Seismic Tremors (named also Non Volcanic Tremors, NVT) have now been well documented and studied in many subduction zones and along some continental fault segments. Recent studies indicate that various phenomenon as Earth and ocean tides, regional and teleseismic earthquakes enhance tremor activity. The increasing number of observations, the coincidence with slow-slip events and the fast migrations of tremors have led to consider frictional slip on the fault interface as the source of tremors. Indeed, laboratory friction experiments succeeded in generating and recording tremor like signals (TLS) (Voisin *et al*., 2008 ; Burlini *et al.*, 2009). Here we demonstrate a systematic correlation between slip acceleration and the emission of TLS in friction experiments. This robust result provide a comprehensive study of how natural seismic tremors might be generated and/or triggered by passing seismic waves, tides or even slow slip events.

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Workshop ESD 2010 is supported by

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ISBN 978-80-89313-49-5