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Workshop on

Numerical Modeling of Earthquake Motions: Waves and Ruptures

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PROCEEDINGS OF THE WORKSHOP
-
ABSTRACT BOOK

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SLOVAK RESEARCH
AND DEVELOPMENT
AGENCY

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There exist disparities among inverted models for the same earthquake although the misfit between data and synthetics has been minimized. Considering the uncertainties in the Green's functions, specifics of fault geometry, and limited spatial coverage, it is unlikely that any inverted source model can resolve the rupture evolution. Using synthetic strong motion data from the Source Inversion Validation Ex. 1 we investigate what features of the rupture can be resolved using finite-fault inversions. The synthetic data were generated from a dynamic rupture with slip weakening friction. We invert for the kinematic parameters of the rupture process using an asymmetric cosine function and a modified Yoffe function, which both produce synthetics that match the data almost perfectly. The total cumulative moment rate function was well constrained, however individual subfault slip rate functions were not well resolved by the inversion process. One bothersome aspect of the dynamic model is the instantaneous rupture of the patch ($\sim 3\times 3$ km^2) around the hypocenter. Our kinematic rupture nucleates at a point in space and evolves from there. This difference leads to timing inconsistencies that are mapped into the kinematic parameters given that the waveforms are matched almost perfectly. These irregularities are particularly visible when we compare the rupture history of the two models in half-second time intervals. During these time windows, the inversion model exhibits slip heterogeneity and a slower rupture front than the target model. Despite these discrepancies, the total cumulative slip distribution of the entire rupture is well resolved. Nevertheless, the fact that two different rupture models can produce identical waveforms is a concern that we aim to investigate further.

DYNAMIC RUPTURE SIMULATION OF THE Mw7.7 BALOCHISTAN EARTHQUAKE – STRIKE-SLIP RUPTURE PROPAGATED ONTO A REVERSE FAULT

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The 2013 Balochistan Earthquake occurred at the junction of a strike slip fault and a reverse fault. Coseismic slip as is constrained by seismic and geodetic observations shows a strike-slip to dip-slip ratio of 6:1. While long term kinematics revealed by fault zone geomorphology shows a systematic variation from strike-slip dominating to dip-slip dominating motion from north to south. By applying dynamic rupture simulations over such a geometrically complicated fault system, we are trying to probe the possibility that dynamic stress can make a fault deviate from its long-term kinematics during an earthquake.

We are using a regional stress field derived from measurements of surface crack orientation distribution, which is indicating a north-south compressional regime in the fault area. We test the dynamic effect caused by the variations in nucleation locations. It only causes second order variations on final slip distribution whether the rupture is nucleating at the reverse fault segment or the strike slip segment under a slip weakening friction law. We further emphasize the dynamic effect by using rate-and-state friction law with strong dynamic weakening where we expect strong effect of dynamic stress on stress-drop directions, that is when dynamic stress caused by strike slip motion passed onto a oblique slip fault segment, it would guide the fault motion to be strike-slip dominating.

THE RELATIONSHIP BETWEEN STRESS DROP AND GMPE EVENT TERMS

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The large variability of crustal earthquake stress drops over several orders of magnitude is not well understood and implies an unrealistically high uncertainty in high-frequency strong ground motion. Stress drop should correlate with the between-event variability (event terms) in ground-motion prediction equations (GMPEs), yet the standard deviation of stress drop is much larger than that of the event terms.

We revisit the relationship between stress drops and GMPE event terms, using the NGA-West2 ground motion database and KikNet data from Japan. To isolate the sources of uncertainty, we consider several metrics for stress drop, including the traditional Brune model, the aRMS stress drop, and a facsimile aRMS based on Arias intensity data. We compare these to PGA event terms from NGA-West2 GMPEs using different record selection criteria to understand how data selection affects population variability.

We attribute the reduced variability observed in the event terms to data quality available in the NGA-West2 dataset, perhaps due to consistent processing, as well as record selection. Because some GMPEs consider the effects of depth, mechanism, and stress drop differences between mainshocks and aftershocks, neglecting to account for these trends when estimating stress drop will necessarily increase the observed variability. We also note that the empirical Green's function deconvolution approach to estimate Brune stress drops shows the least variability of stress drop metrics, and may represent the most accurate method of estimating seismological stress drops. Finally, we consider a particular case when the PGA-event term does not correlate with the earthquake stress drop, which highlights the shortcoming of the event term calculation.

A NUMERICAL ANALYSIS OF AGGRAVATION FACTORS IN TWO-DIMENSIONAL ALLUVIAL VALLEYS

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Numerical simulation tools were used within the framework of the NERA European project to derive "aggravation factors" quantifying the difference between 2D and 1D site responses, and analyse their dependence on geo-mechanical parameters. A comprehensive parametric study involving 972 2D valleys has been carried out, combining 162 triangular and trapezoidal geometries with 6 different velocity profiles. Their geo-mechanical characteristics span a wide range: 500 m - 20 km for width, 30 m to 1 km for thickness, 125 m/s to 500 m/s for VS30, and 2 to 10 for impedance contrast. Their linear response to vertically incident plane SH and SV waves has been computed for 15 different input signals at more than 100 surface receivers, and systematically compared with the 1D response of the local soil columns, so as to derive the modification due to the 2D geometry in terms of 2D/1D "aggravation factors" ("AGF"), for a number of Ground Motion intensity Parameters (GMIP) : pga, pgv, spectral ordinates, energy and duration.

These AGF generally range between 1.3 and 2, with maxima near edges of gently sloping valleys or in the center of embanked valleys, and minima over steeply dipping edges. AGF are parameter dependent, being the largest (up to 3-4) for "energy-related" GMIP, intermediate (around 2) for intermediate period GMIP, and the smallest (below 1.5) for high-frequency indicators. For a given GMIP, highest aggravation factors occur in the center of embanked valleys, steep edge slopes have large but very local effects, gentle edge slopes have significant, long distance effects. AGF are found to decrease with increasing damping, especially for high-frequency GMIP, while they generally increase with decreasing soil stiffness for intermediate to long period GMIP.

GROUND MOTION PREDICTION USING THE AMBIENT SEISMIC FIELD

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Engineering seismologists typically approach the essential task of strong ground motion by fitting intensity observations from earthquakes to Ground Motion Prediction Equations (GMPEs) . In the absence of data from earthquakes, this may be difficult and/or unreliable. Ground motion prediction through simulation is gaining traction as an alternative; however, it requires a tremendous amount of knowledge of Earth structure, and requires high-performance computing capability. We have developed an alternative, hybrid, approach that uses the ambient seismic field to characterize the effect of 3D Earth structure on seismic wave propagation. In this talk we demonstrate that once ambient-field Green's functions are corrected for depth and mechanism, the "virtual earthquakes" that result closely match the recorded waveforms of earthquakes. We show for cases in Japan and California, that we can resolve basin effects, and that we can parameterize basin response in a manner that is suitable for use in GMPEs. Although this is a promising approach, there is still work to do in understanding the source of the ambient-field excitation, and in understanding and modeling nonlinearity. Moreover, there are technical challenges related to the ambient-field Green's functions in developing the 9-component Green's tensor with unbiased amplitudes, pushing the technique to higher frequencies, and discerning body waves in the data. Despite these caveats, the virtual earthquake approach is an important development because it is active, rather than passive, in that we can sample locations of interest by deploying seismic instrumentation. It has the potential to provide essential constraints on ground motion prediction for seismic hazard analysis.

ENERGETIC AND ENERVATED EARTHQUAKES

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We apply empirical Green's function coda-based analysis to earthquakes over a wide range of scales to measure radiated energy, corner frequency and stress drop. We find no systematic dependence of apparent stress or stress drop on seismic moment; however, we find that both apparent stress and stress drop are log-normally distributed. This indicates that although stress is not scale dependent, varies considerably. We identify several anomalous events - both energetic and enervated - that show different spectral signatures from the rest of the population. These events indicate that much of the variation in apparent stress and stress drop is statistically significant, which may have important implications for seismic hazard analysis. In addition to the population of ordinary tectonic earthquakes, we present results for two distinct populations - slow earthquakes and induced earthquakes. Slow earthquakes show dramatically lower stress drop, as has been noted previously, and preliminary results indicate that induced earthquakes have somewhat lower stress drop than tectonic earthquakes. The accurate characterization of stress drop, including its variability, is a key element of seismic hazard analysis.

THE LONG PRECURSORY PHASE OF MOST LARGE INTERPLATE EARTHQUAKES

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It has long been known that many earthquakes are preceded by foreshocks. However, the mechanisms which generate foreshocks and the reason why they occur before some shocks and not others remain mysterious. We show, by analyzing seismic catalogs in some of the world best documented areas, that there is a remarkable contrast between the earthquakes which take place along the interfaces of the tectonic plates and the ones which result from the internal deformation of the plates. Most of the large ($M \geq 6.5$) shallow plate-interface earthquakes which have occurred in the well-instrumented areas of the North Pacific over the past 12 years have been preceded by an acceleration of seismic activity, indicating the presence of foreshocks. The location of these shocks and the contrast observed with intraplate earthquakes, for which foreshocks are less frequent, suggest that the plate interface begins to slip slowly long before it ruptures. In particular, subduction earthquakes seem often preceded by the slow slip of a broad part of the subducting plate. Detailed case studies of the space-time evolution of seismicity before some recent large earthquakes confirm the occurrence of such patterns.

SLOW SLIP, TREMORS, LFES AND TEMPORAL CHANGES OF SEISMIC SPEED IN GUERRERO, MEXICO

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We analyze the relations between slow slip events, tremors, repeating small events (LFE) and temporal changes of seismic velocity. The occurrence of tremors and LFEs is modulated by the occurrence of large SSE in space and time. The detailed analysis of LFEs suggests an along-fault evolution of the pore-pressure during the slow-slip event. We use the extensive catalogue of LFE to define the times when strong activity develops in a specific zone of the subduction interface, up dip the main region of tremor and LFEs permanent activity. This specific region appears to be activated when large SSE events occurs. We use this observation to define potential times of occurrence of smaller SSEs. We use this precise timing produced by seismological data to perform a stack of the noisy GPS time series. We confirm the existence of small SSEs and show their location. Finally we discuss how the temporal evolution of the velocity in the crust could be another proxy for the slow slip at depth, taking into account the correlation between LFE, tremors and SSE.

NUMERICAL QUANTIFICATION OF THE VARIABILITY OF EARTHQUAKE GROUND MOTION IN THE MYGDONIAN BASIN, GREECE

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We present a numerical sensitivy study which aims at better understanding the origin of the variability of earthquake ground motion in the Mygdonian basin near Thessaloniki (Greece).

We use an extended model of the basin (69 km $\times$ 69 km $\times$ 30 km) which was elaborated during the Euroseistest Verification and Validation Project. We compute the 3D visco-elastic response of the basin up to 4 Hz with two independent spectral element codes (efispec and specfem3D), using a robust, semi-automated, mesh design strategy together with a vertical homogenization procedure to define a smooth velocity model of the basin. The final mesh, which does not have to follow any physical interface, contains about 6.5 millions spectral-elements which sizes range from 450 m in the bedrock to 50 m in the sediments, and about 1.3 billion degrees of freedom.

Using reciprocity-based calculations, we build a bank of Green's functions between 15 receivers and 1512 point-sources regularly distributed in distance, depth and back-azimuth from the center of the basin. This synthetic dataset is analyzed for different purposes: First, we study how the ground motion amplification and lengthening of duration caused by the local geology, depend on the location of the sources. Second, we derive classical Ground Motion Prediction Equations from the synthetic data and study how the variability of those predictions is affected by uncertainties in both the source parameters and the site conditions.

RUPTURE PHASE DIAGRAM AND IMPLICATIONS IN EARTHQUAKE PHYSICS

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We have systematically investigated influence of the parameters of slip-weakening law and the size of nucleation asperity on dynamic rupture of a planar fault in full space and half space using boundary integral equation method, in particular, the occurrence conditions for subshear (or sub-Rayleigh for strike-slip rupture) and supershear ruptures. Besides the well-known rupture styles of subshear (or sub-Rayleigh) and supershear, we define a new kind of rupture style in this study, termed the Self-Arresting Rupture, for which the rupture process can be autonomously arrested by itself without any outside interference (e.g., a high strength barrier). Based on the vast number of simulations, we obtained rupture phase diagrams for strike-slip and dip-slip ruptures vertically and obliquely embedded in full and half spaces with different buried depths. The rupture phase diagram clearly illustrates the occurrence conditions of three kinds of rupture styles and the transitions between them. Owing to the influence of the free surface, the rupture in half space becomes much more complicated comparing to the one in full space. For a strike-slip fault with zero buried depth, all ruptures that occur within the parameter range for sub-Rayleigh ruptures in full space case become supershear ruptures. This means that as long as a rupture is able to grow incessantly, it will always evolves into a supershear rupture. For dip-slip faults, however, ruptures will always propagate with subshear speed, although slip rate could be almost twice that of a strike-slip fault. Although the influence of the free surface is strong, it is limited to very shallow ruptures. The rupture phase diagram discussed in this work could provide us a new insight on earthquake rupture mechanics.

INCLUSION OF SCATTERING NOISE INTO GREEN'S FUNCTIONS FOR WAVEFORM INVERSION OF FINITE FAULT SEISMIC SOURCE

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Crustal structure models have greatly improved in recent years for specific regions, such as southern California (Shaw et al., 2015), which in turn has lead to more accurate Green's functions. Still, as one increases the inversion frequency range ($>$0.5 Hz), the level of uncertainty in the Green's functions increases in time (Taborda and Bielak, 2013). This makes the efforts to understand the seismic source process, with a certain level of confidence, more challenging as one increases the desired resolution level. It is noteworthy that the incoherency found in high frequency seismograms can be attributed to the process of scattering (Aki and Chouet, 1975) and scattering energy envelopes at different frequency bands can be calibrated with aftershocks (e.g., Jin et al., 1996). Hence, even though the noise waveform cannot be modeled deterministically, the standard deviation of noise, which changes in time, can be estimated. Simulations are carried to explore the benefits of incorporating this additional information in finite fault source inversions.

SURFACE-WAVE PROPAGATION MODES IN THE VALLEY OF MEXICO: INSIGHTS FROM REALISTIC 3D EARTHQUAKE SIMULATIONS

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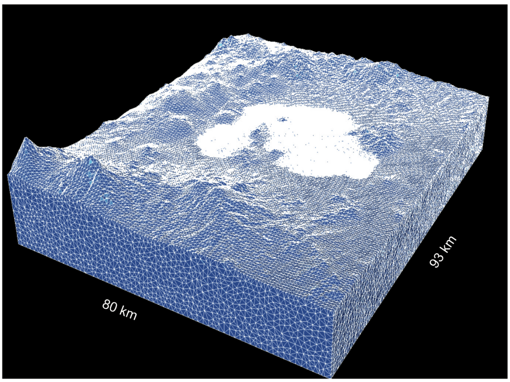
By means of a parallel hp-adaptive discontinuous Galerkin (DG) method (Etienne et al., 2010; Tago et al., 2012) we simulate viscoelastic wave propagation in a 3D basin model of the Valley of Mexico. The model includes both the surface topography (with elevation differences of ∼3,000 m) and the intricate 3D geometry of the sedimentary layers with minimum wave speeds of 50 m/s. The medium is discretized with a tetrahedral mesh where the elements size and interpolation orders are locally adapted to the elastic properties (i.e., to the minimum wavelength) so that the same numerical accuracy is guaranteed everywhere (hp-adaptivity). A large set of earthquake simulations for local events show that: (1) sustained surface-wave trains are generated in the basin edges; (2) first-overtone modes dominate their propagation in the whole basin; and (3) the large intrinsic attenuation of the uppermost layers (compressible clays with ∼30 m thick) is responsible for this propagation regime, especially in shallow basin regions (i.e. less than ∼250 m thick, where most damages concentrated for past earthquakes). Our results are in accordance with borehole seismological observations and provide physical insights to better understand the long duration of ground motions well documented in the Valley of Mexico.



THE NEED OF PHYSIC-BASED GROUND MOTION MODELS FOR HAZARD AND RISK ASSESSMENT OF NUCLEAR POWER PLANTS

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Current practice to assess the seismic hazard assessment in areas where there is not observed data is based on empirical Ground Motion Prediction Equations (GMPEs). But these GMPEs are not constrained by any close data compatible to the expected maximum earthquake size from the site of interest. In addition, the ground motion selection procedures to evaluate the dynamic response of engineering systems for risk mitigation use solely observed data from different seismic sources and locations outside of the site of study. Such observed data are usually scaled in frequency and time domain to artificially fit the maximum expected earthquake size and shaking levels. These procedures to estimate the seismic hazard and ground motion selections essentially extrapolate observed data and empirical models without physical foundations. This is more critical particularly near the source where ground motion is dominated by the source effects, and in areas of geometrical irregularities of the earth structure (basins and topography) where ground motion is dominated by complex wave propagation effects. Therefore it is necessary to provide meaningful procedures for the ground motion prediction in these areas. For that purpose, models that take into account the physics of the rupture and wave propagation appear to be the most suitable approach, in particular, it is important for the detail evaluation of seismic hazard and risk mitigation of future and existing critical structures such as nuclear power plants (NPPs). Here we evaluate the current practice of seismic hazard and ground motion selection for the seismic safety assessment of NPPs located in areas lack of observed data, and we emphasize the need to use physics-based ground motion models for such purpose.

MULTI-SCALE EFFECTIVE FRICTION MODELS FOR FAULT-SCALE DYNAMIC RUPTURE

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Earthquakes span an enormous range of length and time scales, and a major challenge in modeling the physics of earthquakes is developing physics-based models for failure that efficiently capture the physics at a given scale, yet remain tractable for studying rupture at larger scales. Friction models used in dynamic rupture simulations are typically derived from experiments performed at length scales several orders of magnitude smaller than the typical grid spacing used in a dynamic rupture simulation, and thus it remains unclear if present friction models capture the appropriate physics for performing earthquake simulations at the fault scale. We address this problem by studying dynamic rupture on complex faults incorporating physically motivated friction models and use the computed near-fault particle motions to construct scale-appropriate effective friction laws that can be used on coarser resolution numerical grids. This approach ensures that these friction laws capture both the small-scale physical mechanisms in the base friction law as well as the way that the small-scale physics combined with heterogeneity determines the effective friction for a larger fault patch. Our approach is generally applicable to different types of small-scale friction laws, and provides a rigorous framework for translating laboratory-scale work in rock mechanics to fault-scale dynamic rupture models. Our results will ultimately improve our ability to estimate fault-scale ground motions in scenario earthquake simulations using physics-based models.

RADIATED ENERGY OF SHALLOW MODERATE-TO-LARGE EARTHQUAKES

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Radiation of seismic waves during large earthquakes is the most central component of earthquake hazard. Seismic waves record the signature of earthquake dynamic processes. While most earthquakes of M $>$ 5 are recorded on the global seismic network, seismograms are altered by wave propagation through the Earth. The Green's function captures the path effects (attenuation and geometrical spreading) and may be estimated from velocity models of the Earth. Body-wave arrivals are seen most cleanly at angular distances between 30 and 90 degrees, where the effect of the upper mantle discontinuities and core diffraction are minimized. The source pulse width of moderate-to-large shallow earthquakes is larger than arrival time difference between the direct body waves P and S and the depth phases (pP, sP, pS, sS) and, at those steep takeoff angles, destructive interference alters the shape of the recovered source spectra and biases energy measurements. We compare two approaches to measuring radiated energy. First, the total energy is calculated from the sum of individual measurements of energy flux made by correcting for geometrical spreading (e.g., Boatwright 1981). Second, the total energy is measured at single stations by normalizing the source spectrum by the seismic moment and correcting the amplitudes for the averaged radiation pattern. If the Green's functions only remove path effects for the direct phase, both approaches are sensitive to depth-phase interferences and we construct a correction to remove the apparent scaling in scaled-energy with magnitude. We analyze all M $>$ 5 earthquakes shallower than 100 km for the period 1990 to 2015 and calculate their body-wave scaled energy, apparent corner frequency, and high-frequency falloff rate.

3D DYNAMIC RUPTURE SIMULATIONS ACROSS INTERACTING FAULTS: THE Mw 7.0, 2010, HAITI EARTHQUAKE

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The mechanisms controlling rupture propagation between fault segments during a large earthquake are key to the hazard posed by fault systems. Rupture initiation on a smaller fault sometimes transfers to a larger fault, resulting in a significant event (e.g.i, 2002 M7.9 Denali U.S.A and 2010 M7.1 Darfield New Zealand earthquakes). In other cases rupture is constrained to the initial fault and does not transfer to nearby faults, resulting in events of more moderate magnitude. This was the case of the 1989 M6.9 Loma Prieta and 2010 M7.0 Haiti earthquakes, which initiated on reverse faults abutting against a major strike-slip plate boundary fault but did not propagate onto it. Here we investigate the rupture dynamics of the Haiti earthquake, seeking to understand why rupture propagated across two segments of the Léogâne fault but did not propagate to the adjacent Enriquillo Plantain Garden Fault, the major 200 km-long plate boundary fault cutting through southern Haiti. We use a finite element model to simulate propagation of rupture on the Léogâne fault, varying friction and background stress to determine the parameter set that best explains the observed earthquake sequence, in particular, the ground displacement. The two slip patches inferred from finite-fault inversions are explained by the successive rupture of two fault segments oriented favorably with respect to the rupture propagation, while the geometry of the Enriquillo fault did not allow shear stress to reach failure. We also investigate the ground shaking level in this region if a seismic source model, similar to the Mw7.0 2010 Haiti earthquake, occurred on the Enriquillo fault.

RUPTURE AND SEISMICITY DURING MAGNITUDE 7 STICK-SLIP EVENTS OF THE WHILLANS ICE STREAM

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The Whillans Ice Stream, West Antarctica, accomplishes its flow to the sea through tidally modulated stick-slip events. These magnitude 7 (M7) events occur twice daily, producing 0.5 m slip over 100 km in 30 min. Accompanying the M7 events is harmonic tremor, with frequencies between about 10 and 80 Hz that are correlated with ice surface velocity. The tremor likely arises from repeating earthquakes at the bed, as overall ice sliding is intermittently inhibited at small ($\sim$10 m) high strength patches. We study the rupture process of the M7 events and tremor. The unique geometry of the system (involving slip along on horizontal fault, parallel to the free surface and beneath an ice layer that is relatively thin in comparison to the horizontal rupture extent) leads to different scaling relations for the M7 events than for typical tectonic events. We show, for example, that constant stress drop leads not to a constant slip velocity, as in the usual radiation-damping process, but to constant slip acceleration. Using the observed acceleration, we infer a stress drop of only $\sim$3 Pa for the initial rupture phase. Yet scaling relations linking overall slip to rupture length and ice thickness imply a $\sim$300 Pa stress drop. We are exploring several explanations for this discrepancy, and the remarkably long rupture duration, including frictional heterogeneity of the bed (isolated velocity-weakening patches embedded along a primarily velocity-strengthening interface) or the interplay between two weakening mechanisms operating at different slip scales. Insights from this system likely carry over to tectonic settings, such as the rupture dynamics along the shallow portion of subduction plate interfaces (where free surface effects are substantial).

MODELLING AND SEISMIC OBSERVATION OF ROCKFALLS IN THE DOLOMIEU CRATER, PITON DE LA FOURNAISE, LA REUNION

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The seismic and photogrammetric networks of the Piton de la Fournaise volcano (La Réunion Island), maintained by the OVPF, are well appropriate for the study of seismic signals generated by rockfalls occurring in the Dolomieu crater. In particular it makes it possible to relate the rockfall dynamics recorded by the cameras with the time change of the seismic energy. The aim of this study is to better extract the information contained in the seismic signal by comparing the force generated by the rockfall and the work rate calculated using numerical models of rockfalls with the generated seismic power during the rockfall propagation down the slope of the Dolomieu crater. A detailed comparison of the simulated dynamics with the movies of several rockfalls makes it possible to identify the different phases of the flow (initial collapse, impacts and interaction with the topography, stopping phase) and to relate them to the observed seismic signal. Simulations of rockfalls on 2D and 3D topographies obtained by laser-scanner survey of the crater are performed using the thin layer depth-averaged code SHALTOP developed within a collaboration between IPGP and LAMA, Marne-la-Vallée. In particular we test the effect of the friction law (constant friction and volume or velocity weakening friction) on the simulated force and work rate to investigate if the signature of the friction law may be identified on seismic records. After better understanding the seismic signature of rockfalls dynamics we investigate the scaling laws between seismic energy and signal duration for a series of rockfalls in a long period range. In particular we investigate how the parameters of this scaling law change with time and how they are related to the rockfall characteristics (volume, runout, etc.).

DYNAMIC SOURCE INVERSION OF AN INTERMEDIATE-DEPTH EARTHQUAKE: A SLOW AND INEFFICIENT RUPTURE WITH LARGE STRESS DROP AND RADIATED ENERGY

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We introduce a method for imaging the earthquake source dynamics from the inversion of ground-motion records based on a parallel genetic algorithm. The source model follows an elliptical patch approach and uses the staggered-grid split-node method to simulate the earthquake dynamics. A statistical analysis is used to estimate errors in both inverted and derived source parameters. Synthetic inversion tests reveal that the average rupture speed (V_r), the rupture area and the stress drop ($\Delta\tau$) may be determined with formal errors of ∼30%, ∼12% and ∼10%, respectively. In contrast, derived parameters such as the radiated energy (E_r), the radiation efficiency (η_r) and the fracture energy (G) have larger errors, around ∼70%, ∼40% and ∼25%, respectively. We applied the method to the Mw6.5 intermediate-depth (62 km) normal-faulting earthquake of December 11, 2011 in Guerrero, Mexico. Inferred values of $\Delta\tau = 29.2 \pm 6.2$ MPa and $\eta_r = 0.26 \pm 0.1$ are significantly higher and lower, respectively, than those of typical subduction thrust events. Fracture energy is large, so that more than 73% of the available potential energy for the dynamic process of faulting was deposited in the focal region (i.e., $G = (14.4 \pm 3.5) \times 10^{14}$ J), producing a slow rupture process ($V_r/V_S = 0.47 \pm 0.09$) despite the relatively-high energy radiation ($E_r = (0.54 \pm 0.31) \times 10^{15}$ J) and energy-moment ratio ($E_r/M_0 = 5.7 \times 10^{-5}$). It is interesting to point out that such a slow and inefficient rupture along with the large stress drop in a small focal region are features also observed in both the 1994 deep Bolivian earthquake and the seismicity of the intermediate-depth Bucaramanga nest.

	Parameter	Best-fit Model	Average Model
Inverted	$\Delta\tau$	27.7 MPa	29.2 ±6.2 MPa
	$\Delta\tau_n$	58.5 MPa	60.0± 7.9 MPa
	D_c	0.71 m	0.74 ± 0.11 m
	$\Delta\mu$	0.036	0.03± 0.005
	A	78.4 km^2	88.5± 18.0 km^2
Derived	M_0	5.75 x 10^{18} Nm	(9.54 ± 2.27) x 10^{18} Nm
	D_f	1.45 m	1.45 ± 0.21 m
	V_r/V_S	0.38	0.47 ± 0.09
	G	14.5 x 10^{14} J	(14.4 ± 3.5) x 10^{14} J
	E_r	3.1 x 10^{14} J	(5.4 ± 3.1) x 10^{14} J
	η_r	0.18	0.26 ± 0.10
	K	0.84	1.01 ± 0.22

Inverted and derived source parameters for the M6.5 intermediate-depth Zumpango earthquake, Mexico.

COMPREHENSIVE ANALYSIS OF THE 2009 TONGA-SAMOA EARTHQUAKE

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The mechanism and rupture process of the 2009 Tonga Mw 8.1 earthquake remain controversial. This event produced tsunami waves with localized regions of ∼12 meter run-up that caused 192 casualties. In addition to the GCMT solution, several models have been proposed to explain the observations. Lay et al. (2010) found evidence for a normal-faulting mainshock, closely followed by two triggered reverse-faulting events. Beavan et al. (2010) proposed a two-fault model, with a slow-slip event at the subduction zone leading up to a normal-faulting mainshock. Kiser & Ishii (2012) argued that there are at least two subevents composing the earthquake, which are spatially focused around the epicenter. The large variations among these models indicate that the event requires more investigation. The exact locations of any triggered subevents have important implications about future hazards in this region. Here we utilize both high- and low-frequency far-field seismic observations to study the rupture process. Back-projection and compressive sensing are performed using global stations to understand the spatial and temporal evolution of the earthquake. The full azimuthal coverage eliminates possible stacking artifacts and provides precise locations for high-frequency energy bursts. Long-period data are used to solve for CMT solutions to understand the mechanism, while an improved multiple moment tensor method is also applied.

QUANTIFYING CAPABILITY OF A LOCAL SEISMIC NETWORK IN TERMS OF LOCATIONS AND FOCAL MECHANISM SOLUTIONS OF WEAK EARTHQUAKES

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Extension of permanent seismic networks is usually governed by a number of technical, economic, logistic and other factors. If the planned upgrade of the network can be clearly justified by theoretical assessment of the network capability in terms of reliable estimation of the key earthquake parameters (e.g. location and focal mechanisms) it could be useful not only for scientific purposes but also as a concrete proof during the process of acquisition of the funding needed for upgrade and operation of the network. This paper presents suggestion of a combination of suitable methods and their application to the Little Carpathians local seismic network (Slovakia, Central Europe) monitoring epicentral zone important from the point of seismic hazard. Three configurations of the network are considered: 13 stations existing before 2011, 3 stations already added in 2011, and 7 new planned stations. Theoretical errors of the relative location are estimated by a new method, specifically developed in this paper. The resolvability of focal mechanisms determined by waveform inversion is analyzed by a recent approach based on 6D moment-tensor error ellipsoids. We consider potential seismic events situated anywhere in the studied region, thus enabling 'mapping' of the expected errors. Results clearly demonstrate that the network extension remarkably decreases the errors, mainly in the planned 23-station configuration. The already made 3-station extension of the network in 2011 allowed for a few real-data examples. Free software made available by the authors, enables similar application in any other existing or planned networks.

LARGE-SCALE EARTHQUAKE DYNAMIC RUPTURE SCENARIOS ON NATURAL FAULT ZONES

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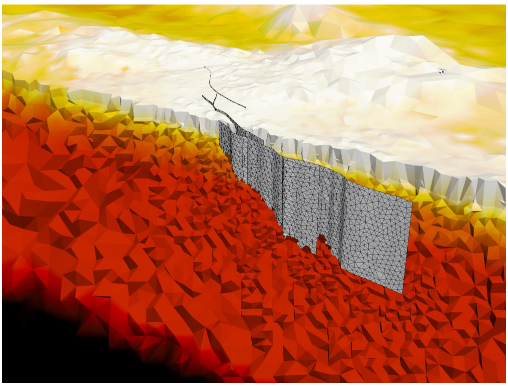
We present results from forward models of large-scale earthquake scenarios with initial conditions constrained from geological observations, geophysical data and geomechanical modelling. The models incorporate high fidelity dynamic rupture evolution and ground motion frequencies (up to 10 Hz) based on the 1992 Northridge, the 1994 Landers events and a tsunamigenic setup. Through consideration of a variety of different representations of natural complexity, our results imply that the rupture dynamics depend specifically on the local background stress state concurrently with fault geometry.

We have utilised the recently optimised version of SeisSol – an arbitrary high-order derivative Discontinuous Galerkin (ADER-DG) scheme – to solve the spontaneous earthquake rupture problem with high-order accuracy in both space and time on three-dimensional unstructured tetrahedral meshes.

SeisSol now obtains petaflop performance on modern, massively parallel hardware and was chosen as one of the Gordon Bell Prize Finalist Applications in 2014. This work highlights the benefits of using state-of-the-art numerical methods and high-performance computing for fundamental earthquake physics and physics-based ground motion modelling.



FRACTURE-MECHANICS-BASED ESTIMATES OF MAGNITUDE OF INDUCED EARTHQUAKES

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This work is a first step towards a more complete integration of earthquake physics and rupture dynamics into a theoretical and computational framework for modeling induced and triggered seismicity. Empirical relations for a maximum magnitude of induced earthquake lack a physics-based relation between earthquake size and the characteristics of the triggering stress perturbation consistent with current models of the earthquake rupture process. To fill this gap, we will extend our recent results on the nucleation and arrest of dynamic ruptures derived from fracture mechanics theory. In our previous work, we derived theoretical relations between the area and overstress of overstressed asperity and the ability of ruptures to either stop spontaneously (sub-critical ruptures) or runaway (super-critical ruptures). These relations were verified by comparison to 3D dynamic rupture simulations on faults governed by slip-weakening friction. Krammer et al. (2015) used similar arguments to successfully predict the relation between rupture arrest distance and external loading in laboratory experiments in which frictional sliding is nucleated by localized stresses. Here, we apply and extend these results to situations that are representative of the induced seismicity environment. We present physics-based predictions of the rupture arrest area and we compare them with the results of 3D dynamic rupture simulations. We investigate various scaling relations to obtain magnitude from rupture area. We discuss implications for the maximum magnitude of induced earthquakes as a function of amount of injected volume or time history of injection, as well as the dependence of stress drop of induced events as a function of distance to the injection well.

INITIATION OF DYNAMIC RUPTURES IN NUMERICAL SIMULATIONS

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Galis et al. (2015) performed an extensive parameter study to investigate critical parameters using numerical simulations of 3D dynamic ruptures under linear slip-weakening friction law on planar faults with homogeneous friction and material parameters. They found excellent agreement between critical area estimated by Uenishi (2009) and their numerical results for high background stress and between their estimate A_2 and numerical results for low background stress. However, their study was limited to an overstressed asperity (i.e., initial traction inside the asperity is set higher than static traction). We generalize their approach and investigate critical area and overstress using constant initial traction on a fault with lower normal traction inside the asperity (and consequently the static traction inside the asperity is lower than the initial traction). We also investigate applicability of the generalized estimates to initiate ruptures on faults with heterogeneous parameters and on rough faults. We also investigate initiation using extended asperities and asperities of irregular shapes.

MODELING VELOCITY RECORDINGS OF THE MW6.0 SOUTH NAPA, CALIFORNIA, EARTHQUAKE: UNILATERAL EVENT WITH WEAK HIGH-FREQUENCY DIRECTIVITY

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The Napa earthquake occurred on 24 August 2014 in California, causing one fatality and damaging many older buildings in the Napa area. The event has been recorded by many stations at near-fault distances. Published slip models suggest that the rupture propagated up-dip and unilaterally along the fault, making the earthquake a unique opportunity to test kinematic source models with various directivity strengths. We first perform slip inversion using the method by Gallovič et al. (2015), employing low frequency data (0.05-0.5 Hz) and a 1D velocity model. Then we generate broadband synthetics (0.05-5Hz) using the advanced Ruiz Integral Kinematic (RIK) source model (Ruiz et al., 2011). The RIK model is composed of randomly distributed overlapping subsources with fractal number-size distribution. The particular distribution of the RIK subsources is controlled by the low-resolution inverted slip model. Besides providing omega-squared spectral decay at high frequencies, the RIK model reproduces frequency-dependent directivity effects with various strengths. In particular, the rupture model with the weakest high-frequency directivity provides velocity waveforms with the smallest modeling bias and variance. We also simulate ground motions taking into account the 3D velocity structure of the area (USGS 3D model). Results indicate important differences in terms of peak values and waveform complexity for most of the receivers. In particular, the spatial complexity of the velocity model can result in large reverberations, sometimes more developed than in the recordings. As differences between the 1D and 3D simulations are also present at low-frequencies to some extent, we perform the slip inversion using 3D Green's functions based on the approach of Gallovič et al. (2015).

CHANGES IN SEISMICITY AND STRESS LOADING ON SUBDUCTION FAULTS IN THE KANTO REGION, JAPAN, 2011 - 2014

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Seismic activity has increased in the Kanto region, Japan, following the 2011 M9.0 Tohoku earthquake. We here reassess this increase up to June 2014, to show that normal, Omori-like relaxation characterizes the activity on crustal faults as well as on the Philippine Sea plate, but not on the deeper Pacific plate. There, repeating earthquakes display a two-fold rate of occurrence (still on going in June 2014) as compared to the pre-Tohoku rate, suggesting enhanced creep. We compute the Coulomb stress changes on the upper locked portion of the Philippine Sea plate, which last ruptured in 1923. We find that this fault was little affected by either the co-seismic, the post-seismic, the accelerated creep, or the 2011 Boso silent slip event.

GROUND MOTIONS DUE TO EARTHQUAKES ON CREEPING FAULTS

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We investigate the peak ground motions from the largest well-recorded earthquakes on creeping strike-slip faults in active-tectonic continental regions. Our goal is to evaluate if the strong ground motions from earthquakes on creeping faults are smaller than the strong ground motions from earthquakes on locked faults. Smaller ground motions might be expected from earthquakes on creeping faults if the fault sections that strongly radiate energy are surrounded by patches of fault that predominantly absorb energy. For our study we used the ground motion data available in the PEER NGA-West2 database, and the ground motion prediction equations that were developed from the PEER NGA-West2 dataset. We analyzed data for the eleven largest well-recorded creeping-fault earthquakes, that ranged in magnitude from M5.0-6.5. Our findings are that these earthquakes produced peak ground motions that are statistically indistinguishable from the peak ground motions produced by similar-magnitude earthquakes on locked faults. These findings may be implemented in earthquake hazard estimates for moderate-size earthquakes in creeping-fault regions. Further investigation is necessary to determine if this result will also apply to larger earthquakes on creeping faults.

Please also see:

Harris, R.A., and N.A. Abrahamson (2014), Strong ground motions generated by earthquakes on creeping faults, Geophysical Research Letters, vol. 41, doi:10.1002/2014GL060228.

SEISMO-MECHANICAL MODELLING: EARTHQUAKE SUPERCYCLES AND IMPLEMENTATION OF RATE-AND STATE-DEPENDENT FRICTION

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Our goal is to explore the cause-and-effect relationships between subduction dynamics and the megathrust earthquake potential. Therefore we develop a continuum mechanics-based seismo-mechanical modelling approach that bridges the gap between the simulation of processes on geodynamic and earthquake time scales. Our numerical model including a strongly rate-dependent friction formulation was validated (Van Dinther et al. 2013) against scaled analogue subduction experiments (Corbi et al. 2013).

Here we present the results of an application of this model to study the role of the seismogenic zone downdip width for the megathrust earthquake cycle in subduction zones (Herrendoerfer et al. 2015). Our results suggest that supercycles – a long-term cluster of differently sized megathrust earthquakes – occur more likely in wide seismogenic zones. A greater width increases the average excess of strength over stress and thus favors the occurrence of several partial ruptures, which ultimately lead up to a complete rupture at the end of a supercycle. In contrast, ordinary cycles of mainly complete ruptures occur in narrower seismogenic zones ($<$120 km). This is supported by observations insofar as supercycles have been proposed to occur in seismogenic zones that are wider than average (111 km).

We are currently working to overcome the limitations of our model approach. Here we also present the implementation of rate-and state-dependent friction (RSF). We show results of the interseismic locking and event properties in our models with RSF and compare them with analogue experiments for a range of subduction velocities.

GROUND MOTION MODELLING OF AN ALPINE FAULT EARTHQUAKE FOR THE SOUTH ISLAND (NEW ZEALAND)

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The large September 2010 and the tragic February 2011 Canterbury earthquakes caused widespread damage by ground shaking and sand liquefaction in the Canterbury region. Both earthquakes were less than 50 km from the Christchurch central business area and had a magnitude that is much smaller than that expected from the Alpine Fault (Mw=8.2). Recent advances in earthquake mechanics allow us to compute seismograms for realistic earthquake scenarios, at specific locations, and with specific site conditions. Such simulations can provide very useful alternative estimates of possible ground motions from large faults for major population centres in the South Island (NZ).

Synthetic broadband strong-motion records are produced for a possible large Alpine Fault earthquake (Mw8.2) at selected population centres that may be strongly affected. We compute seismograms using a hybrid approach combining a simple discrete wavenumber approach and a stochastic method. To define the earthquake sources, we apply the validated recipe based on a characterised source model for large crustal earthquakes developed by Irikura and Miyake (2011). The synthetic rock site motions are then used as the input motion for a frequency-dependant site amplification function.

The synthetic records show that near-source ground motion accelerations in main West-Coast towns of the South Island are expected to exceed 20%g during an Alpine fault earthquake, while ground motions in Christchurch are expected to be moderate, with peak ground accelerations (PGAs) of 8%g. This high near-source PGA will need further modelling as it is likely due not only to non-linear soil response not accounted for in this study but also to the presence of a modelled asperity nearby and to strong directivity effects.

THE POTENTIAL FOR SUPERSHEAR RUPTURE AND ENHANCED GROUND MOTION IN DAMAGED FAULT ZONES

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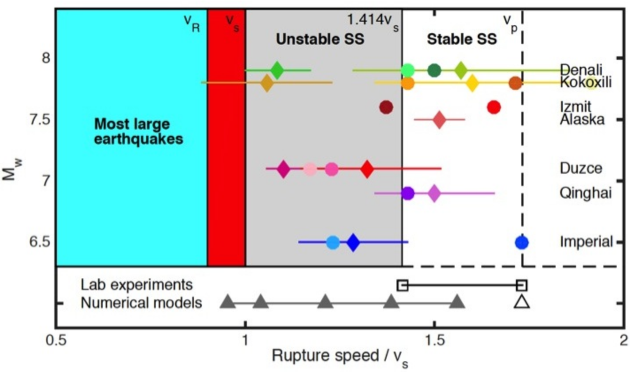
It is observed that strike-slip earthquakes usually propagate at speeds slower than the Rayleigh wave speed (v_R) but occasionally jump to speeds faster than the S wave speed (v_s), or supershear speeds. Both theoretical studies of dynamic fractures and laboratory experiments conducted in a homogeneous medium find supershear ruptures can propagate steadily at speeds between $\sqrt{2}v_s$ and v_p, referred to as stable supershear. Ruptures in the unstable supershear speed range ($v_s < v < \sqrt{2}v_s$, gray patch in the figure) would either accelerate rapidly to stable supershear or decelerate to sub-Rayleigh speed. However, a compilation of supershear ruptures inferred from past large earthquakes (color circles and diamonds with bars in the figure) shows that both unstable and stable supershear speeds can occur in nature.

We propose that this discrepancy between dynamic fracture theories and seismic observations possibly arises from the previous consideration of the fault zone as a homogeneous medium. In contrast, natural faults are usually surrounded by damaged rocks characterized by low seismic velocities. We find in dynamic rupture simulations that supershear transition in damaged fault zones can be triggered by fault zone head waves and can occur at background stresses lower than those required in a homogeneous medium. Moreover, the unstable supershear speeds become stable when supershear earthquakes rupture in damaged fault zones. We also apply the analysis of P-wave spectra and V_p/V_s ratio inversion to the source region of 2003 Big Bear, CA sequence and find a supershear aftershock was likely to rupture through a damaged fault zone featured by an anomalously low V_p/V_s ratio compared to the surrounding region.



MULTI-METHOD SYSTEMATIC APPROACH TO NON-VOLCANIC TREMOR DETECTION IN THE SAN JACINTO FAULT, CALIFORNIA

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Investigation of the relationship between tremor, earthquakes, and transient deformation may provide insight into stress dynamics, fault mechanics, and may improve our ability to assess seismic hazard. We have compiled a catalog of tremor-like events from along San Jacinto Fault (SJF), California; verified with three techniques. Our results show signal resembling non-volcanic tremor (NVT) in two regions near the SJF. Visual inspection of MAOTECRA seismic data from March to July 2011 revealed a preliminary set of NVT candidates. Emergent signals are seen in windows of $\sim$100-400s. Tests alternating frequency bands rule out different energy sources, (i.e. local, regional and teleseismic events, train, and anthropogenic noise). We applied a multi beam-backprojection algorithm (Ghosh et al., 2009) to detect additional tremor candidates and validate previous detections, determine azimuth to source, and depth. Resulting beams indicate two discrete locations of NVT-like signals – one southeast and one northwest of the Anza Gap, the latter of which corresponds with the triggered tremor locations identified by Wang et al., 2013 following the 2002 Denali earthquake. Low slowness of NVT candidate beams suggests a deep source, helping to rule out a surface noise source, (i.e. wind farms or trains). Lastly, an envelope cross correlation (ECC) technique are applied to further elucidate NVT candidates with regional network stations. After cross-referencing the ANSS earthquake catalog, preliminary ECC results show an average of 117 mins/day of tremor-like signal surrounding the Anza Gap in June, 2011. We plan to perform additional ECC and beamforming (when array data is available) over a longer time period to detect additional tremor candidates and expand our existing catalog.

NUMERICAL MODELING OF THE NUCLEATION PROCESS OF LABORATORY EARTHQUAKES

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It has been shown that the onset of frictional instability is characterized by a transition from stable, quasi-static rupture growth to unstable, inertially-controlled high-speed rupture. In particular, quasi-static rupture nucleation prior to the onset of frictional instability has been well imaged in recent laboratory stick-slip experiments (e.g., Latour et al., 2013; Svetlizky and Fineberg, 2014). However, the mechanism governing the rupture nucleation has been widely debated. Here we investigate the process of rupture nucleation observed in laboratory experiments using numerical simulations of earthquake sequences that incorporate dynamic elasticity and rate-and-state friction laws. Our simulations quantitatively reproduce observed nucleation processes under different confining pressures. Propagation distances at the quasi-static to dynamic rupture transition can be well predicted by theoretical estimates of the nucleation size. Our results suggest that fracture energy (sometime referred to as breakdown work) controls the growth of nucleating rupture in laboratory experiments. The sensitivity of rupture evolution to the model parameters further suggests that the propagation speeds of nucleating rupture reported in laboratory experiments are also sensitive to friction properties and loading conditions. We discuss implications of the results for the nucleation process of earthquakes in nature.

STATISTICAL PROPERTIES OF SOURCE, PATH, AND SITE OF FOURIER SPECTRA AND RESPONSE SPECTRA FROM THE GENERALIZED SPECTRAL INVERSION OF STRONG GROUND MOTIONS

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We investigated the characteristics of strong ground motions separated from acceleration Fourier spectra and Response spectra calculated from moderate ground motions observed by K-NET, KiK-net, and the JMA Shindokei Network in Japan using the generalized spectral inversion method. The separation method used the outcrop motions at YMGH01 as reference where we extracted site responses due to shallow weathered layers. We include events with magnitude equal to or larger than 4.5 observed from 1996 to 2011. We find that our frequency-dependent Q values are comparable to those of previous studies, and that the obtained Q values depend on the traveling regions. From the corner frequencies of source spectra, we calculate Brune's stress parameters and found a clear magnitude dependence, in which smaller events tend to spread over a wider range while maintaining the same maximum value. We confirm that this is exactly the case for several mainshock-aftershock sequences. The average stress parameters for crustal earthquakes are much smaller than those of subduction zone, which can be explained by their depth dependence.

We also separated the strong motion characteristics based on the acceleration response spectra successfully. However, the separated characteristics of strong ground motions of both results are different, especially in the lower frequency range less than 1Hz. These differences comes from the difference between Fourier spectra and response spectra found in the observed data; that is, predominant components in high frequency range of Fourier spectra contribute to increase the response in lower frequency range with small Fourier amplitude because strong high frequency component acts as an impulse to a Single-Degree-of-Freedom system.

COMBINATION OF NUMERICAL METHODS FOR SIMULATION OF SEISMIC WAVE PROPAGATION IN COMPLEX MODELS

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To accurately simulate seismic wave propagation and ground motion it is necessary to account for a wide range of complexities in the Earth structure its surface topography. Thin layering, fluid-filled microsturcutes, destructed fault zones etc. leads to anisotropic, viscoelstic models on meso- and macroscopic scale. Simulation of wave propagation in such models requires the use of the advanced computationally intense computational techniques. However, zones with complex physical properties are typically localized in space, thus it is reasonable to implement advanced approaches only locally, where they are needed, whereas to use the computationally efficient technique such as standard staggered grid scheme in the main part of the model.

We present an ongoing research on combination of the different numerical techniques in one algorithm to make it flexible and able to account the complex physical properties of the media but be computationally cheap. In particular, to account for the small scale heterogeneities a local time-space mesh refinement is used, to deal with anisotropy a partially staggered grid scheme (Lebedev scheme) is applied locally, to account the free-surface topography discontinuous Galerkin method is utilized in the upper part of the model.

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THE EFFECT OF STRESS PERTURBATION ON THE SEISMICITY OF A HETEROGENEOUS RATE-AND-STATE FAULT

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Induced seismicity may be studied within the framework of rate-and-state dependent friction. Murphy et. al (2013) have shown that fluid injection near (but outside of) an active heterogeneous tectonic fault, represented by reducing the normal stress on the fault, may induce change in its seismicity. Specifically, they have shown that injecting fluid near a fault undergoing a quasi-periodic seismic cycle may result in increasing the size of the upcoming earthquake, as well as time advancing its arrival. On the other hand, Gallovic (2008) showed that stress perturbations might actually delay the occurrence of the next event depending on the timing of the stress perturbation within the earthquake cycle. However, Gallovic (2008) considered a smooth, homogeneous model, which is not realistic for real faults. In our present study, we use a quasi-dynamic model of finite 2-D fault with heterogeneous distribution of rate-and-state dependent friction parameters and Gutenberg-Richter seismicity in order to revisit both studies and systematically explore the effect of fluid injection on fault dynamics.

NUMERICAL STUDY OF SITE EFFECTS IN A CLASS OF LOCAL SEDIMENTARY STRUCTURES

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We present results of an extensive numerical study of site effects in a class of 7 local surface sedimentary structures. The study is a part of the effort of the international project SIGMA – SeIsmic Ground Motion Assessment - organized jointly by EDF, AREVA, CEA and ENEL in 2011-2015. One working group of the project is primarily focused on improvement of local site conditions representation. Our study aims in investigation of potential of a few specific site typologies to be prone to significant amplification effects, estimation of these effects using 1D, 2D and 3D numerical simulations, identifying key structural parameters responsible for site effects, and identifying the key characteristics of earthquake ground motion. The selected sites include the Mygdonian basin, Greece, – a shallow sediment-filled basin, Grenoble valley, France, – a typical deep Alpine sediment-filled valley, and four sediment-filled valleys - two small, one mid-sized and one relatively large. In addition to these nominal models we investigated also a set of their modification in order to estimate effects of variations of structural parameters. Based on the direct finite-difference numerical simulations and a set of selected representative recorded accelerograms we calculated amplification and aggravation factors for 10 characteristics of earthquake ground motion. We analyzed values of the calculated quantities for hundreds of theoretical receivers using statistical methods.

MULTICYCLE SIMULATIONS OF EARTHQUAKE RUPTURE IN REGIONS WITH COMPLEX FAULT GEOMETRY

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The stressing conditions on faults continuously evolve due to several factors, such as tectonic stressing, fault interactions, pore-fluid perturbations, and viscoelastic relaxation. Landmark investigations of en echelon fault interaction with uniform initial stresses that promote super-shear rupture reported successful jumps occur at step-over widths $\leq$2.5 and 5 km for compressional and extensional stepovers, respectively (Harris and Day, 1993). However, the initial stressing conditions have a profound effect on the rupture process.

We use the 3D quasi-dynamic, physics-based simulator RSQSim to investigate how stress evolution effects rupture propagation at fault stepovers over multiple earthquake cycles. Comparisons of single-event ruptures at fault stepovers between RSQSim and the dynamic finite element code FaultMod demonstrate nucleation locations on the secondary fault similar to those of Harris and Day (1993). Multi-cycle event simulations incorporating rate- and state friction on en echelon faults using evolved stress states that arise due to fault interaction and tectonic loading are presented here. Results indicate that successful rupture jumps only occur at stepover widths of 1-1.5 km for both fault step types. The spatial pattern of rupture re-nucleation locations is influenced by the evolved stresses and is dissimilar to previous studies. Finally, initial rupture nucleation always occurs before the magnitude of the pre-stress reaches values high enough to cause super-shear rupture. These results suggest that mechanisms such as extreme weakening may play a larger role than initial stress on supershear ruptures, and that observations of rupture jumps $>$ 1 km may be explained by fault connection at depth.

A CASE FOR HISTORIC JOINT RUPTURE OF THE SAN ANDREAS AND SAN JACINTO FAULTS

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The earthquake of 8 December 1812 ruptured the San Andreas Fault from Cajon Pass to at least as far north as Pallet Creek (Biasi et al., 2002). The 1812 rupture has also been identified in trenches at Burro Flats to the south (Yule and Howland, 2001). However, the lack of a record of 1812 at Plunge Creek, between Cajon Pass and Burro Flats (McGill et al, 2002), complicates the interpretation of this event as a straightforward San Andreas rupture. Paleoseismic records of a large early 19th century rupture on the northern San Jacinto Fault (Onderdonk et al., 2013; Kendrick and Fumal, 2005) allow for alternate interpretations of the 1812 earthquake.

I use dynamic rupture modeling to investigate possible rupture paths for the 1812 earthquake. I find that the scenario which best matches paleoseismic data, records of damage to missions, and distributions of precariously balanced rocks, is one in which northward-directed rupture on the San Jacinto Fault jumps onto the San Andreas Fault and propagates bilaterally. This promotes continued energetic northward rupture on the San Andreas, due to directivity and stress transfer from the initial rupture reaching the end of the San Jacinto. This also decreases Coulomb stress south of Cajon Pass, which lowers the energy of the rupture and may inhibit it from reaching the surface at Plunge Creek.

While it cannot be definitively said that this, or any other, rupture progression is what actually occurred in 1812, joint San Andreas-San Jacinto rupture is consistent with paleoseismic and historical data. This has implications for the possibility of future multi-fault rupture within the San Andreas system, as well as for interpretation of other paleoseismic events in regions of complex fault interactions.

TWO END-MEMBER MODELS OF SLOW-SLIP EVENTS AND COMPLEX TREMOR MIGRATION PATTERNS

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Slow-slip events (SSE) and tectonic tremors reveal a broad spectrum of earthquake behavior at the bottom of seismogenic fault zones. Here we present two end-member models that reproduce complex tremor migration patterns observed in Northern Cascadia, including large-scale forward tremor migration and Rapid Tremor Reversals (RTRs). Both models involve a heterogeneous fault composed of brittle asperities embedded in a creeping matrix. In model A, friction in the matrix features a weakening-to-strengthening transition at high slip velocity, which leads to spontaneous SSEs that drive tremors. In model B, friction in the matrix is velocity-strengthening and complex tremor swarms result solely from the interaction between brittle asperity failures via their intervening post-seismic creep (in the absence of tremor asperities this model produces no SSE). Both models reproduce the scale and recurrence interval of large tremor episodes, and the migration speed and distance of RTR observed in Cascadia. Model B is simpler and produces ratios of RTR to forward migration speeds that match observations better. Observations of tremor-genic and tremor-less slow slip occurring in a same segment of the Cascadia subduction zone suggest that natural faults are in between these two end-member models. The overall fault criticalness (its ability to produce spontaneous transient events) in model B is further studied through analytical and numerical methods. We find that a fluid pressure reduction in the velocity-weakening asperities can bring the fault to a supercritical state (generating spontaneous transients) even if the asperities are individually subcritical (steadily creeping if unperturbed). Implications for the depth-dependency of earthquake behavior will be discussed.

UNCERTAINTY QUANTIFICATION AND QUALITY APPRAISAL FOR FINITE-FAULT EARTHQUAKE SOURCE INVERSIONS

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Finite-fault source inversions estimate kinematic rupture parameters of earthquakes using a variety of available data sets and inversion approaches. Rupture models are obtained by solving an inherently ill-posed inverse problem, subject to numerous a priori assumptions and noisy observations. Despite these limitations, near real-time source inversions are becoming increasingly popular, while we still face the dilemma that uncertainties in source inversions are essentially unknown. Yet, the accurate estimation of earthquake rupture properties, including proper uncertainty quantification, is critically important for earthquake seismology and seismic hazard analysis, as they help to adequately characterize earthquake complexity across all scales.

The “Source Inversion Validation” (SIV) project (http://equake-rc.info/sivdb) is a collaborative international multi-institutional effort to examine current state-of-the-art in earthquake source inversion, and to develop and test novel source inversion approaches. Through a series of benchmark exercises of varying degree of complexity, we test inversion methods, and evaluate their performance through different comparative metrics. We also quantify the intra-event variability in rupture models, which is evident for past earthquakes in the SRCMOD database (http://equake-rc.info/srcmod), and propose metrics to rank earthquake rupture models.

In this presentation, I will summarize the SIV-efforts and the latest results, and I will describe several quantitative metrics that we have developed to quantify the similarity (or dissimilarity) of kinematic source properties (e.g. slip on the fault) that help to assess the quality and model robustness of finite-fault source models.

ADVANCED SEISMIC MICROZONING OF THE COMPLEX SEDIMENTARY BASIN OF MARTIGNY (SWITZERLAND) BY TWO-DIMENSIONAL AKI-LARNER METHOD AND THREE-DIMENSIONAL SPECTRAL-ELEMENT METHOD

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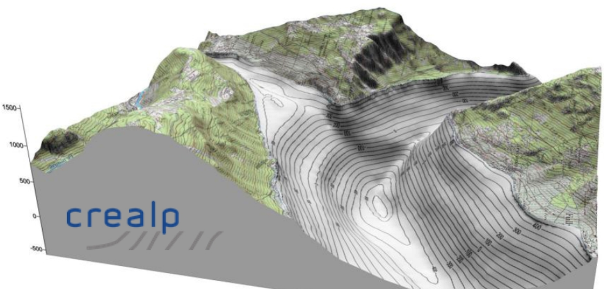
The region of Martigny (Valais, Switzerland) is located at the confluence of two ancient Alpine glaciers: the Rhone and Dranse glaciers. Such a confluence had for consequence the creation of a deep, steep-sided and complex three-dimensional (3D) valley reaching 1 km depth and spreading 3 km wide (at maximum, see Figure 1). The valley is filled with quaternary sediment formations whose shear-wave velocity structure has been determined by geophysical campaigns performed during former projects (e.g., geothermal prospection): the shear-wave velocities range from 250 m/s at the shallowest formation to 1350 m/s at 1 km depth. The underlying seismological bedrock's shear-wave velocity has been approximated to 3000 m/s. In order to determine elastic response spectra for the future seismic microzoning of the region, the "Centre de Recherche sur l'Environnement Alpin" (CREALP) mandated three institutes to perform two- and three-dimensional advanced numerical seismic wave propagations to quantify the complex basin's seismic response and its associated uncertainties. This presentation aims at showing: i) the semi-automatic meshing/refining technique developed for arbitrary 3D sedimentary basin surrounded by steep topography, ii) the medium homogenization technique to include arbitrary 2D sediment/bedrock interface in a 3D finite-element mesh and iii) the results obtained by a 2D Aki-Larner method code and two spectral-element method codes (SPECFEM3D and EFISPEC3D).



A SPECTRAL ELEMENT DISCRETIZATION ON UNSTRUCTURED TETRAHEDRAL MESHES FOR ELASTODYNAMICS

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Spectral finite element methods (SEM) defined over quadrilateral and hexahedral element geometries have proven to be a fast, accurate and scalable approach to study wave propagation. In the context of regional scale seismology and rupture dynamics simulations, the geometric restrictions associated with hexahedral elements limit the applicability of the classical SEM to study such scenarios.

Here we describe a spectral element discretization defined over unstructured meshes composed of triangles or tetrahedra. This method possesses the spectral accuracy and dispersive properties of a spectral element method, together with the geometric versatility provided by unstructured meshes. The use of a spatially adaptive discretiation allows us to resolve complex geometries without compromising solution quality.

The success of such a development for 3D applications hinges upon: (i) choosing the coordinates of the basis function so as to minimize the condition number of the Vandermonde matrix for a given polynomial order (p); (ii) selecting an appropriate quadrature rule; (iii) the development of an efficient solver for the mass matrix. We describe these aspects and verify the accuracy of the method in 2D and 3D using manufactured and analytic solutions. A solver for the mass matrix system is introduced which exploits both matrix free matrix-vector products and optimized matrix-matrix products (e.g. DGEMM). The convergence of the solver is found to be only weakly dependent on the polynomial order for the range commonly used in production applications ($4 \leq p \leq 6$).

Lastly, we comment upon the applicability, efficiency and accuracy for elastodynamics in comparison to established methods.

GEOMETRY AND PORE PRESSURE SHAPE THE PERIOD-MULTIPLYING TREMORS ON THE DEEP SAN ANDREAS FAULT

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Observations of tectonic tremors and their association to aseismic slip challenge our understanding of the dynamics of faulting. In particular, the long record of tremors on the deep San Andreas Fault near Parkfield, with its complex pattern of doublings and halvings of recurrence times still eludes explanations. The tremor pattern was regularly oscillating with a period doubling of 3 and 6 days from mid-2003 until it was disrupted by the 2004 Mw 6.0 Parkfield earthquake. But by the end of 2007, the previous pattern resumed.

Here, we show that a single asperity with homogenous frictional properties can produce different faulting mechanisms in the same area. Our three-dimensional model is based on rate-and-state friction with a single velocity-weakening patch embedded in a velocity-strengthening region. Non-circular asperities may produce an alternating sequence of slow-slip events and regular earthquakes under a certain range of geometrical and frictional properties in the same area in a wider stability range than circular asperities.

We use these findings to explain the period doubling of the Parkfield tremors. We assume that the tremors are due to slip on micro-asperities triggered by slow-slip events and earthquakes alike in a single, much larger asperity. We simulated the tremor sequence of thousands of slip events in a self-consistent model assuming that the post-seismic transient is caused by effective pore-pressure variations.

Our results illustrate the importance of aseismic processes in the history of fault slip evolution. Better understanding of the mechanics of slow-slip events will be paramount to turn observations into useful earthquake warnings.

EXTRACTING RUPTURE VELOCITIES AND RUPTURE ENERGY FROM NEAR FIELD SEISMIC RECORDS

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Theoretical studies suggest that the dynamic variations of near-field shear strain scaled by the average phase velocity follow closely the ground velocity. This can be used to extract rupture velocities of large strike slip earthquakes that penetrates a shallow low velocity layer. Recent experiments also indicate that analytical solutions for dynamic mode II crack can be used to estimate from near-fault waveform data the fracture energy of the propagating rupture. These two method will be applied to seismic waveforms recorded in the near field of large strike-slip earthquakes (e.g., the 1999 M7.1 Duzce and 2011 M7.2 El Mayor-Cucapah) to extract rupture velocity and fracture energy of the events.

APPLICATION OF SEISMIC ARRAY PROCESSING TO TSUNAMI EARLY WARNING

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Recent tsunami disasters of the oceanic events have revealed the need for early warning so that coastal populations evacuate. Tsunamis generated by the 2004 M9.3 Sumatra and 2011 M9.0 Tohoku earthquake killed close to a quarter million people. Current tsunami alert systems, relying on earthquake source inversion based on direct tsunami waveforms measured by the DART buoys and teleseismic body-wave seismic recordings, are of limited effectiveness for near-field tsunami warning, because the tsunami wave arrives to the local coast before the data is collected. Here, we explore the concept of characterizing rupture model in real-time using onshore dense seismic arrays. Back-tracing array seismic waveforms allow estimating the rupture extent, which leads to the construction of simple slip models as the input of forward tsunami simulations. We implement it in a simulated real-time environment and analyze the Tohoku earthquake rupture recorded by the Hi-net network. The obtained results are consistent with teleseismic earthquake source imaging results and yield reasonable estimates of rupture area, moment and average slip. This source information can be acquired within 6 minutes after the earthquake, which could facilitate a timely tsunami warning. The predicted arrival time and wave amplitude achieve a reasonable fit to the observations. We propose to develop an automatic warning system that provides rapid near-field warning for areas of high tsunami risk. The initial focus will be in Japan and Pacfic Northwest, where dense seismic network are established with the capability of real-time data telemetry and open data accessibility. We plan to test and validate the proposed approach on either historical large tsunamigenic earthquakes or realistic synthetic tsunami scenarios.

APPLICATION OF A HYBRID APPROACH FOR BROADBAND GROUND MOTION SIMULATIONS TO THE 2008 IWATE-MIYAGI NAIRIKU EARTHQUAKE

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A hybrid procedure is developed merging the full-wave low-frequency signals with stochastic high-frequency synthetics to simulate broadband strong ground motion for engineering applications. The synthetic seismograms are computed utilizing a deterministic approach in the low frequency range (COMPSYN) while a stochastic procedure (EXSIM) is applied to generate the signals in the high frequency range. The stochastic synthetics are rescaled and combined with the deterministic signals applying weighting functions at intermediate matching frequency.

We validated our approach reproducing, within the known source and velocity model constraints, the Kik-NET and K-net accelerometric data recorded during the 2008 Iwate-Miyagi Nairiku earthquake (Mw 7.0).

The results show that this procedure is able to simulate satisfactorily the observed waveforms and the related response spectra over the broadband frequency range. To valuate the effects of the hybridization in the peak and spectral parameters we calculated the goodness of fit: if we use the low-pass filtered recordings instead of deterministic calculated seismograms, the overall fit improves, evidencing that a good reproduction of low frequencies is necessary to obtain reliable results even in the high frequency range. Peak ground velocities are well reproduced by our approach; peak ground accelerations show larger discrepancies due to the intrinsic characteristics of the stochastic model and the small-scale heterogeneity that affect the seismic radiation and propagation at high frequencies.

SENSITIVITY OF GROUND MOTION TO KINEMATIC RUPTURE PARAMETERS FOR EARTHQUAKES IN THE WASATCH FAULT ZONE, UTAH

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We develop ninety-six kinematic rupture models of M7 earthquakes on the Salt Lake City segment (SLCS) of the Wasatch fault zone and carry out 3-D finite-element earthquake simulations to investigate the effect of source parameters on long-period (T$\geq$1 s) ground-motions. Rupture models are developed using a method that produces ground motions consistent with the empirical NGA-West1 database and with the objective of investigating the effect of variations in the realization and correlation length of the slip field, hypocenter location, average rupture velocity and slip velocity. Parameter values are consistent with observed M7 normal-faulting earthquakes.

The resulting ground motions largely agree with the mean and variability indicated by empirical ground motion prediction equations (GMPEs), but the ground motions are highly sensitive to the rupture parameters. On average, rupture and slip velocity have the greatest effect on ground motion, with strong dependencies on the measurement frequency. The slip-field realization and hypocenter location contribute to substantial spatial variability in ground motion. Correlation length perturbations also give rise to increased spatial variability, though with reduced amplitudes compared to the slip realization and hypocenter parameters.

The high sensitivity of simulated ground motions to the rupture parameters highlights the need for improved knowledge about the earthquake source, including improvements to the methodologies for developing rupture models and for characterizing source parameters. Accurate computation of ground motion variability, which is an important component of the seismic hazard calculations, will require increased knowledge about the underlying distributions and covariances among rupture parameters.

STRONG MOTION RECORDS AND 3D PHYSICS-BASED NUMERICAL SIMULATIONS OF THE Mw6.0 MAY 29 2012 PO PLAIN EARTHQUAKE, ITALY

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Stimulated by the recent advances in computational tools for the simulation of seismic wave propagation problems in realistic geologic environments, we present a 3D physics-based numerical study for simulation of earthquake ground motion in the Po Plain, during the MW 6.0 May 29 2012 earthquake.

This study required a sequence of investigations, from the analysis of a large set of near-source records, to the calibration of an improved kinematic seismic source model, up to the development of a 3D numerical model of the portion of the Po Plain interested by the earthquake, including the irregular buried topography, with sediment thickness varying from few tens of m to some km. The spatial resolution of the numerical model is suitable to propagate up to about 1.5 Hz. Numerical simulations were performed using the open-source high-performance code SPEED, based on the Discontinuous Galerkin Spectral Elements Method.

The 3D numerical model proved successful to reproduce with reasonable accuracy, measured through quantitative goodness-of-fit criteria, the most relevant features of the observed ground motion both at the near- and far-field scales. These include: (i) the large fault normal velocity peaks at the near-source stations driven by up-dip directivity effects; (ii) the small-scale variability at short distance from the source, resulting in the out-of-phase motion at stations separated by only 3 km distance; (iii) the propagation of prominent trains of surface waves, especially in the Northern direction, induced by the irregular buried morphology in the near-source area; (iv) the map of earthquake-induced ground uplift with maximum values of about 10 cm, in substantial agreement with satellite measurements.

MICROMECHANICS BASED OFF-FAULT PERMEABILITY EVOLUTION DURING EARTHQUAKES

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We investigate the role of off-fault damage and damage-enhanced off-fault permeability on earthquake nucleation on faults surrounded by a relatively high pore fluid pressure. This mimics a situation in which wastewater, injected in a reservoir, diffuses towards a fault. First, we develop a micromechanical model for permeability evolution in brittle materials that are strain rate sensitive. We extend the micromechanical model developed by Bhat et al. (2012) in which the constitutive description of a brittle material is governed by micro-cracks to relate damage and inelastic strains. This allows evaluating the micro-cracks aperture, plugged into Gueguen and Dienes (1989) to find the permeability. Additionally, we present preliminary results on the role of off-fault dynamic permeability changes on earthquake nucleation by solving the coupled dynamic rupture propagation and pore fluid pressure diffusion.

SIMULATION OF SEISMIC-WAVE PROPAGATION DURING THE 1927 M_L 6.25 JERICHO EARTHQUAKE

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The Dead Sea Transform (DST) is the main seismic source in Israel and neighboring countries capable of producing up to M 7.5 earthquakes known from geological, archeological and historical records. However, due to low seismicity rate, strong earthquakes and their ground motions were not recorded in Israel. The last major earthquake on the terrestrial part of the DST was the M_L 6.25 July 11, 1927 Jericho earthquake and the most destructive earthquake in the region during the 20th century. Estimations of casualties range between 250–500 deaths and 400–700 injuries. Many buildings were damaged, landslides and rockfalls were observed and the flow of the Jordan River had stopped for 21.5 h.

In absence of recorded ground motions we concentrate our efforts on forward numerical modeling to estimate the ground motions during strong earthquakes. We use the Distributed Slip Model (DSM, Shani-Kadmiel et al., 2014), a kinematic, generic, finite fault source with a smooth “pseudo-Gaussian” slip distribution on an elliptical rupture patch to initiate seismic-wave propagation.

In this study we calculate MSK (Medvedev et al., 1965) and MMI (Wood and Neumann, 1931) intensities which are compared with 132 intensity records, based on physical evidences and reports compiled by Avni et al., (2002) and re-evaluated by Zohar and Marco (2011) to account for local site-attributes. Preliminary results based on a laterally homogeneous velocity model, suggest that (a) contrarily to previous studies, the fault ruptured from south to north, and (b) topographic and directivity effects explain most of the data.

RUPTURE DYNAMICS AND GROUND MOTIONS FROM 3-D DYNAMIC ROUGH-FAULT SIMULATIONS OF DIP-SLIP EVENTS

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Natural faults during their evolutionary stages manifest varying degrees of geometrical complexities over a broad range of length scales. Following Shi and Day (2013), we perform 3-D numerical simulations of dynamic rupture along rough dip-slip faults to study the properties of rupture dynamics and patterns of resultant ground motions in dip-slip events. Dynamic rupture propagation on rough faults results in rupture irregularities that lead to ground motions with complex spatial patterns and extensive high-frequency content. We explore the effects of source- and path-effect-related model parameters on the properties of ground motions including medium scattering and attenuation, fault dip, depth to the top-of-rupture and stress condition. We found period-dependence characteristics of ground-motion patterns (e.g., hanging-wall effect) due to different physical mechanisms at play that include rupture directivity, closeness to maximum surface displacement and radiation patterns. In addition, we attempt to reproduce past notable historic dip-slip events such as the 1994 Northridge events and make meaningful comparisons between the synthetic data and field records in order to gain a better understanding of the roles of different physical parameters in the generation process of ground motions.

INVERSION FOR THE STRESS CONDITIONS OF THE 2014 NAPA VALLEY, CALIFORNIA AND THE 2004 PARKFIELD, CALIFORNIA EARTHQUAKES

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The improvements of computer capabilities have allowed transitioning from a kinematic inversion approach (i.e., inferring the distribution of slip-rate functions on a fault) to a dynamic inversion approach (i.e. inferring the distribution of stresses on a fault). This has the advantage to offer a physics-based approach to study earthquake source processes. At the same time, the inversion procedure allows testing of thousands of different stress models and their capability to explain the observations. Here, we show results for the 2014 Mw6.0 Napa Valley, California and the 2004 Mw6.0 Parkfield, California, earthquakes. The dynamic inversions are carried out using the elliptical sub-fault approximation in which the stress conditions are described within elliptical patches that have variable positions and sizes on the assumed fault plane. For both earthquakes, we use strong-motion accelerograms ($<$30 km away from the fault) integrated into displacement and filtered between 2 to 10 s. Although the modeling approach smooths out details of the inferred rupture, it still captures the low-frequency part of the observed waveforms. The low parameterization of the method ($\sim$20 parameters) allows a robust investigation of the details for the explored parameter-space. The inversion finds a stress distribution that leads to a seismic moment and an average rupture speed close to the kinematic analysis of the two earthquakes. Both earthquakes show a similar ratio $\sim$1.5 between strain change per unit area of fault surface and energy release rate. The main difference between the two earthquakes is the stress-drop — a larger stress-drop ($\sim$10 MPa) for the rather compact rupture of the Napa Valley earthquake and a lower stress-drop ($\sim$4MPa) for the wider rupture of the Parkfield earthquake

INFLUENCE OF FAULT GEOMETRIC HETEROGENEITIES ON THE DYNAMIC RUPTURE PROCESS

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Fault heterogeneities are known to generally hinder the dynamic earthquake rupture process, leading to slower or less extended events. Different kinds of heterogeneities can be considered: e.g., heterogeneities in the initial stress distribution, in the frictional characteristics, in the elastic properties of the medium close to the fault. In this study, we investigate the effect of geometric heterogeneities on the dynamic rupture process of rough faults using Seissol, a code based on an Arbitrary High Order Discontinous Galerking Method (ADER-DG). The ability of the ADER-DG method to accurately simulate a rupture propagating on a rough fault is first discussed using results from a recent SCEC/USGS benchmark. The effects of geometric fault heterogeneities are then quantified by testing different scales of roughness, including small scale fractal roughness as well as larger scale fault bending, by varying the wavelength range and the amplitude of the heterogeneities. Finally, we aim to put into perspective the conclusions of this parametric study by considering the effects of other sources of heterogeneities.

ADVANCED MOMENT-TENSOR INVERSION CODE

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Focal mechanisms are important for understanding seismotectonics of a region, and they serve as a basic input for seismic hazard assessment. Usually, the point source approximation and the moment tensor (MT) are used. We are developing a new, fully automated tool for full-waveform MT inversion taking into account recent developments in the field. It includes automated data retrieval, data selection according to noise level and presence of various instrumental disturbances, and setting frequency ranges for each station according to its distance, noise, and event magnitude. The MT inverse problem is solved in a space-time grid whose size is automatically chosen according to the location uncertainty and magnitude. Green's functions are calculated in parallel. Full data covariance matrix are included, so the noisy frequencies are filtered out. Stations are weighted according their azimuthal coverage and signal power. Simultaneously with the MT solution, uncertainty and reliability of the result is also evaluated using condition number. The software is tested on a dataset from the Swiss seismic network and the results are compared with the existing high-quality MT catalog. It is programmed as much versatile as possible in order to be applicable in other regions and for events ranging from local to regional. It shares some similarities with the broadly used ISOLA software in terms of the inversion methods and input/output file structures, but most codes have been re-written from the scratch for maximum computational efficiency. Opposed to ISOLA, whose advantage is in a friendly manual processing of individual events using Matlab GUI, the new codes are intended rather for (i) massive automated application on large sets of earthquakes and/or (ii) near real-time applications.

DYNAMIC RUPTURE SIMULATIONS ON COMPLEX FAULT ZONE STRUCTURES WITH OFF-FAULT PLASTICITY USING THE ADER-DG METHOD

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In dynamic rupture models, high stress concentrations at rupture fronts have to to be accommodated by off-fault inelastic processes such as plastic deformation. Incorporating plastic yielding can significantly reduce earlier predictions of ground motions. But the effects of an inelastic material response on the key aspects of earthquake physics are still not known in detail, especially not on complex fault geometries.

We present an implementation of off-fault-plasticity and its verification for the software package SeisSol, an arbitrary high-order derivative discontinuous Galerkin (ADER-DG) method. For the nonelastic calculations we impose a Drucker-Prager yield criterion in shear stress with a viscous regularization. We verify the implementation by comparison to the SCEC/USGS Spontaneous Rupture Code Verification Benchmarks. Additionally we explore the numerical characteristics of the off-fault plasticity implementation by performing convergence tests and discussing the localization of plastic strain.

The ADER-DG method is especially suited for complex geometries by using unstructured tetrahedral meshes. In this context we investigate the effects of off-fault-plasticity on a branched fault zone structure simulating the 1992 Landers earthquake. We compare the scenario with purely elastic material properties to one using plastic yielding. Including plasticity influences the step-over times and localizations of the rupture jumps in the dynamic simulation. Further, we want to investigate the effect of off-fault plasticity on the floor uplifting in a tsunamigenic subduction zone scenario.

EVOLUTION OF RUPTURE STYLE WITH TOTAL FAULT DISPLACEMENT: INSIGHT FROM METER-SCALE DIRECT SHEAR EXPERIMENTS

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We report results with Indian metagabbro (Vs=3.62 km/s) that are obtained from a series of meter-scale direct shear experiments conducted at NIED. We focus on strain gage array data of stick-slip events loaded with 0.01 mm/s and under 6.7 MPa normal stress and find the following: (1) During the early stage with relatively intact fault surface, ruptures mainly behave as a slow propagation mode (10 to 100 m/s). (2) With the accumulation of total fault displacement, grooves indicative of strongly coupled local patches (i.e., asperities) are generated along the sliding surface, which are primarily elongated along the loading direction and are accompanied by notable gouge formation. At this stage, rupture speeds start to increase but are still below the shear wave speed. (3) After long enough total fault displacement (e.g., more than 400 mm), grooves of a sufficient amount and length are generated. The corresponding ruptures show, following an initial nucleation phase, fast propagation with speed comparable to the shear wave speed. Detailed strain data analysis suggests that the above rupture style evolution is associated with an increasing efficiency either in storing elastic strain energy or in releasing the stored strain energy along the synthetic fault. The former may be attributed to the growing groove density that dictates the net coupling of the fault, while the latter may be facilitated by powder lubrication (Reches and Lockner, 2010) associated with gouge formation. Our study highlights the role of displacement-dependent fault surface properties in controlling the propagation style of dynamic ruptures. It also calls for the need to conduct large-scale friction experiments over long displacement to better approximate natural fault conditions.

LABORATORY INVESTIGATION OF SLIP MODE ALONG A BIMATERIAL (GABBRO/MARBLE) FAULT INTERFACE: PRELIMINARY RESULTS AND IMPLICATIONS

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We conduct a series of meter-scale direct shear experiments along a gabbro/marble fault interface at NIED. Unlike the transitional behavior from stick-slip to stable sliding along a marble/marble interface under 1.3 MPa normal stress and 0.01 mm/s loading rate, the bimaterial case shows persistent stick-slip behavior under the same loading conditions as well as under 2.6 MPa normal stress in subsequent tests. Visual observations of the damage pattern reveal quite different features between the marble/marble case and bimaterial case. For the marble/marble case, the generated grooves typically show a low aspect ratio between loading-parallel and loading-perpendicular directions, suggesting that some diffusional deformation is effective during slip. In contrast, the corresponding grooves for the gabbro/marble case still show preferred growing direction parallel to loading, similar to what has been observed along a gabbro/gabbro interface. Detailed observation further reveals that gabbro asperities can penetrate into the softer marble sample and can be partially sheared off during ruptures. Supportive strain array data show that the apparent friction before failure at these locations is high or even above 1, confirming the contribution from gabbro asperities. These results highlight the role of discrete brittle asperities in generating stick-slip fault behavior in a surrounding ductile-like environment. An analogous natural example may be found by the role of seamount in generating earthquakes through or underneath sediments in subduction zones (Cloos, 1992). We are currently working on the strain array data to analyze the detailed rupture process during failure. More results will be presented during the meeting.

INVESTIGATION OF EARTHQUAKE RUPTURE DIMENSION THROUGH SEISMIC INTERFEROMETRY

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Understanding earthquake source properties is essential for improving our knowledge of earthquake source physics. The earthquake source dimension is one of the most elementary source parameters but among the most difficult to be directly constrained. Taking advantage of the recent developments of large-scale regional seismic arrays (e.g., USArray) and seismic interferometry, we propose to examine earthquake source dimensions through data-mining the waveform coherency as a function of inter-station distance. We systematically analyzed the waveform coherency of 102 deep and intermediate teleseismic events recorded by USArray in different frequency bands. We find that the coherency of relatively small earthquakes (M$\sim$6) is high across the USArray over inter-station distances $>$10 wavelengths and up to 2 Hz, which indicates a minimal 3D structural effect on the waveform coherency. However, for big earthquakes (M$>$7), we observe significant inter-station coherence fall off with faster decay rates for larger magnitudes. For the same earthquake, coherence falls slower along the ray-path than across it. We hypothesize that these patterns are governed by a finite source effect. We verified this hypothesis by establishing the analytical solution of inter-station coherency of a 1D rupture embedded in a 2D medium. We derived a multi-variable relationship to systematically measure the earthquake source dimension based on inter-station coherency. Our preliminary results of the deep earthquakes in the sea of Okhotsk are consistent with rupture dimension revealed by back-projection studies. This relationship may potentially further constrain other source properties, such as aspect ratio and rupture speed that remain difficult to determine by conventional approaches.

DYNAMIC RUPTURE PROCESS OF 2008 Mw7.9 WENCHUAN EARTHQUAKE WITH NON-PLANAR FAULT AND IRREGULAR SURFACE

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Enough investigations and observations have been undertaken suggesting that the great 2008 Mw 7.9 Wenchuan earthquake ruptured as a much complex pattern. The causative fault of Wenchuan earthquake has complex geometry, divided into several segments with few kilometers offset. Moreover, topography around the rupturing area varies intensively. Adding with other complex circumstances, it is a challenge to model the dynamic rupture of this earthquake closing to the reality. In this research, we simulated the source dynamics of the 2008 Mw7.9 Wenchuan Earthquake of China by using the 3D curved grid finite-difference method. The influences of complex geometry of fault as well as the strongly varying topography on rupture process are investigated through rupture dynamic simulations. In our simulation, uniform background tectonic stress field are assumed, and slip-weakening law with homogeneous friction coefficients are utilized. We found that the typical heterogeneous spatial distribution of final seismic slip on the fault can be generated by the realistic non-planar complex geometry of fault surface. If an appropriate geometry is chosen, the main feature of the kinematic source rupture process and final slip distribution, derived from the inversion of seismic waves and geodetic data, could be reproduced. We found that rupture front is significant affected by the non-planar fault and free surface.

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