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Theoretical Constraints on Large Earthquake Ground Motion

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Abstract

Our investigations on Theoretical Constraints on Large Earthquake Ground Motion have focused on the following research directions: (1) Developing a seismic representation theorem that includes, in addition to the standard moment term, a damage-related term stemming from changes of elastic moduli in the source region. (2) Calculations of energy partition between radiation and dissipative mechanisms in various model realizations. (3) Incorporation of thermodynamically-based continuum damage rheology into models of dynamic rupture. Finally, to better quantify properties of ground motion we also worked on (4) Analysis on polarization of amplified ground motion near fault zones. The research topics contribute complementary information for developing limits to large ground motion that may be generated by earthquakes. The most striking theoretical result is that reduction of elastic moduli in the source volume is shown to be capable of increasing significantly the radiation to the bulk. The most interesting observational result is that amplified ground motion near fault zones is shown to be polarized in the approximate fault-normal direction, likely reflecting reduced stiffness normal to the fault due to cracking with predominant fault-parallel orientation. Below we provide additional details on the main results associated with each research directions.

(1) Seismic radiation from regions sustaining material damage (*Ben-Zion and Ampuero, 2009*)

We derived analytical results for seismic radiation during rapid episodes of inelastic brittle deformation that include, in addition to the standard moment term, a damage-related term stemming from changes of elastic moduli in the source region. The radiation from the damage-related term is associated with products of the changes of elastic moduli and the total elastic strain components in the source region. Order of magnitude estimates suggest that the damage-related contribution to the motion in the surrounding elastic solid, which is neglected in standard calculations, can have appreciable amplitude that may in some cases be comparable to or larger than the moment contribution. A decomposition analysis shows that the damage-related source term has an isotropic component that can be larger than its double-couple component. Remarkably, the analytical results indicate that decreasing elastic moduli in the source region, as produced generally by brittle deformation of low-porosity rocks, increase the seismic radiation to the bulk compared to standard estimates based only on the moment source. In contrast, increasing moduli in the source region, which may be produced during the formation of compaction bands in porous rocks, decrease the radiation.

(2) Slip modes and partitioning of energy during dynamical frictional sliding between identical elastic-viscoplastic solids (*Shi, Needleman and Ben-Zion, 2010*)

The effect of plasticity on dynamic frictional sliding along an interface between two identical elastic-viscoplastic solids is analyzed. The configuration considered is the same as that in Coker et al. (2005) except that here plane strain analyses are carried out and bulk material plasticity is accounted for. The specimens have an initial compressive stress and are subject to shear loading imposed by edge impact near the interface. The material on each side of the interface is modeled as an isotropically hardening elastic-viscoplastic solid. The interface is characterized as having an elastic response together with a rate- and state-dependent frictional law for its inelastic response. Depending on bulk material

properties, interface properties and loading conditions, frictional slip along the interface can propagate in a crack-like mode, a pulse-like mode or a train-of-pulses mode. Results are presented for the effect of material plasticity on the mode and speed of frictional slip propagation as well as for the partitioning of energy components between stored elastic energy, kinetic energy, plastic dissipation in the bulk and frictional dissipation along the interface. Some parameter studies are carried out to explore the effects of varying the interface elastic stiffness and the impact velocity.

(3) Interaction between dynamic rupture and off-fault brittle damage *(Xu, Ben-Zion, Ampuero and Lyakhovsky, 2011)*

The generation of off-fault damage during earthquake ruptures can have several important, partially-conflicting, implications for the maximum expected ground motion. The yielding above a given level of motion corresponding to the elastic limit, and absorption of energy in the damage generation process, should reduce the amplitude of the ground motion. However, the reduction in the values of the elastic moduli in the damaged off-fault region can amplify locally the motion and create a waveguide that may allow the motion to propagate with little geometric attenuation. Moreover, the reduction of elastic moduli in the damage zone may produce dynamically bimaterial interfaces that can reduce the frictional dissipation and increase the radiation efficiency.

Several recent studies have incorporated plastic yielding in simulations of dynamic rupture (e.g., Andrews, 2005; Ben-Zion and Shi, 2005; Andrews et al., 2007; Templeton and Rice, 2008). However, these models keep the elastic moduli in the yielding region unchanged, so they do not account for the above (potentially important) *feedback mechanisms* between damage generation and properties of dynamic ruptures and ground motion. To account for these effects, we incorporated in a model of dynamic rupture the continuum brittle damage rheology of Lyakhovsky and Ben-Zion (2008) and earlier related works for the evolution of elastic moduli in regions where the elastic limit is exceeded. Our work so far focused on verifying the code by calculating energy components associated with frictional heat, seismic radiation, off-fault plasticity and damage, and ensuring that energy conservation is strictly satisfied. Having completed this task successfully, we made some initial comparisons between properties of simulated dynamic ruptures, near-fault motion and energy partitioning with corresponding simulations in a model having plasticity and those having brittle damage in the bulk. All calculations so far were made with parameters that *limit the amount of damage* to prevent off-fault brittle instabilities (which would become additional sources of radiation).

The results obtained so far can be summarized as follows. The location and extent of the yielding zone are found to depend on the direction of the maximum compressive background stress in agreement with Templeton & Rice (2008), and on the crack vs. pulse mode of rupture in agreement with Andrews (2005) and Ben-Zion & Shi (2005). The off-fault yielding zone is wide-spread for conditions representing shallow depth, and becomes progressively localized for conditions representing deeper section in agreement with Ben-Zion & Shi (2005), Ma & Andrews (2010) and observations. For crack-like rupture, the intensity of damage increases along the fault and decreases normal to the fault as in Andrews (2005). For pulse-like ruptures, the intensity varies along fault in relation to the slip velocity, and also decays normal to the fault over more limited width, in agreement with Ben-Zion & Shi (2005). The intensity for both rupture modes is

enhanced when associated with larger regional stress, but the width can be suppressed by higher confining pressure. The angle representing expected microcrack orientations is shallow on the compressional side of the fault and steep on the extensional side. The angle is steep at shallow depth and gradually decreases with depth. A velocity contrast across the fault modifies the above features by producing steeper angles on the compliant side compared to the stiffer side for situations representing the same quadrant (compressional or extensional).

Continuing work on this topic will perform more realistic/challenging simulations with damage parameters that allow off-fault brittle instabilities that become additional sources of radiation. After verifying the code again by ensuring that energy conservation is strictly satisfied, we will compare the properties of the simulated dynamic ruptures, near-fault motion and energy partitioning with corresponding simulations in a model having plasticity rather than brittle damage in the bulk. We also plan to examine the possible existence of bimaterial effects and wrinkle like slip pulses due to *spontaneous* generation of co-seismic off-fault damage. Additional important continuations related to research topic (1) above are as follows. (a) Compare the generated source mechanisms with the effective "observed" source properties that would be inferred by standard analysis of the radiated waves. (b) Examine the radiated fields for signatures (radiation patterns of *P* and *S* waves, relative amplitudes of isotropic and deviatoric radiations, additional seismic phases) that can be used to distinguish the damage-related radiation from other potential origins of complex non-double-couple mechanisms.

(4) Horizontal polarization of ground motion in the Hayward fault zone at Fremont, California: Dominant fault-high-angle polarization and fault-induced cracks ***(Pischiutta, M., F. Salvini, J. Fletcher, A Rovelli and Y. Ben Zion, 2011)***

We investigate shear-wave polarization in the Hayward fault zone near Niles Canyon, Fremont, CA. Waveforms of 12 earthquakes recorded by a seven-accelerometer seismic array around the fault are analyzed to clarify directional site effects in the fault damage zone. The analysis is performed in the frequency domain through H/V spectral ratios with horizontal components rotated from 0 to 180°, and in the time domain using the eigenvectors and eigenvalues of the covariance matrix method employing three component seismograms. The near-fault ground motion tends to be polarized in the horizontal plane. At two on-fault stations where the local strike is N160°, ground motion polarization is oriented N88°±19° and N83°±32°, respectively. At third on-fault station the motion is more complex with horizontal polarization varying in different frequency bands. However, a polarization of N86°±7°, similar to the results at the other two on-fault stations, is found in the frequency band 6-8 Hz. The predominantly fault-normal polarized motion at the Hayward fault is consistent with similar results at the Parkfield section of the San Andreas fault and the Val d'Agri area (a Quaternary extensional basin) in Italy. Comparisons of the observed polarization directions in several cases with models of fracture orientation based on the fault movement indicate that the dominant horizontal polarization is near-orthogonal to the orientation of the expected predominant cracking direction. The results help to develop improved connections between fault mechanics and near-fault ground motion.

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