Deterministic Modeling of Physically-Limited Ground Motion

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When predicting ground motion at critical structures for very low probability of exceedance, Probabilistic Seismic Hazard Analysis can yield values much larger than any ground motion that has actually been observed in an earthquake. Are there physical limits that can constrain such predictions? Two physical principles can be applied: (1) maximum stress drop available at the source, and (2) strength of material through which waves propagate. These two principles are applied in this work to deterministic forward modeling of an earthquake on the Solitario Canyon fault near the Yucca Mountain repository. A schematic diagram of the site is shown in Figure 1.

Strength of material provides a physical constraint on ground motion. Particle velocity propagated in an S wave is limited to shear strength divided by shear impedance, which effectively limits short-period motion, even though velocity can increase further as waves reverberate in a layer. Non-elastic response near the earth's surface constrains short-period motion. In addition, non-elastic response near a rupture front increases fracture energy and limits particle velocity at the source.

To establish physical limits on earthquake ground motion, we need to use non-linear calculational methods. The demonstration calculation shown here is done in two-dimensional plane strain. I propose to generalize the computer code to three dimensions in the coming year.

The state of stress in the crust, at least at shallow depths, has been determined from bore-hole measurements by Zoback and others. The least compressive principal stress is horizontal, and its ratio to the vertical stress is consistent with a coefficient of Coulomb friction of 0.6 on a normal fault dipping 60 degrees. The fluid pressure is hydrostatic below the water table, which is about 600 m below the surface. I assume that this stress state extends to a depth of 10 km. Shear stress on the fault in this initial stress state is shown as a cyan curve in the left panel of Figure 2.

Unfortunately, we know little about limits on stress drop. Complete stress drop may be possible. Thermal pressurization of pore fluid from frictional heating can produce near-complete stress drop in large events in sufficiently impermeable material. The character of ground motion near the northern part of the rupture of the Chi-chi earthquake suggests that thermal pressurization may have occurred there. In this work I arbitrarily assume that friction drops to a value of 0.1 after the initiation of slip. Slip starts when shear stress rises to a level corresponding to static friction of 0.7.

Results from a dynamic elastic calculation done with these stress assumptions are shown in Figure 2. Final slip resulting from the assumed stress drop is 15 m. Geologic evidence suggests that slip greater than 3m has very small probability on the Solitario canyon fault. In future work the large stress drop used here might be confined to small patches, which would limit slip but not reduce the intensity of shorter-period motion.

The calculation is repeated using the Mohr-Coulomb yield condition shown in Figure 3. The cohesion of 1 MPa is a compromise between larger cohesion measured in the welded tuff units and very small cohesion on fractures and joints. The final plastic strain distribution is shown in Figure 4. The along-fault component of plastic strain is extensional in the down-thrown block, and is compressive at the site of the repository.

Figure 5 compares velocity at the repository site between the elastic and non-elastic calculations. Yielding reduces peak horizontal velocity, and it significantly reduces spectral response velocity shown in the lower right panel.

Yielding is not as effective in reducing ground motion in this calculation as it would be in a more realistic case. Because of the large stress drop over the entire fault surface, the rupture propagates at the P-wave speed. The large initial motion at the site is a P wave, and no yielding occurs until a reflection arrives from the surface. If large stress drop occurred only on small patches, rupture velocity would be slower, and motion at the site would be primarily shorter-period S waves. For these reasons yielding would be much more effective in reducing the motion. In future work large stress drop will be confined to patches, such that slip conforms to geologic evidence.

Conclusions are (1) strength of geologic materials sets limits on ground motion; (2) non-elastic calculations are required. Methods for non-elastic calculations are well-established outside the disciplines of seismology and engineering seismology. I have knowledge and experience to apply such methods to seismological problems.

Proposed work:

A. **Code development.** A 3D non-elastic code, appropriate to dynamic fault rupture, will be developed. Features will include topography, structure varying across faults, initial stress in equilibrium with topography and density structure, Coulomb yielding, tensile failure, spall, and compaction. **Time required**: one to two man-years.

B. **Running calculations.** Sources and material properties must be varied in a comprehensive study to maximum physical ground motion. **Time required**: one to two man-years.

Tasks A and B can be concurrent if more than one person is supported. First results can be available in less than a year.

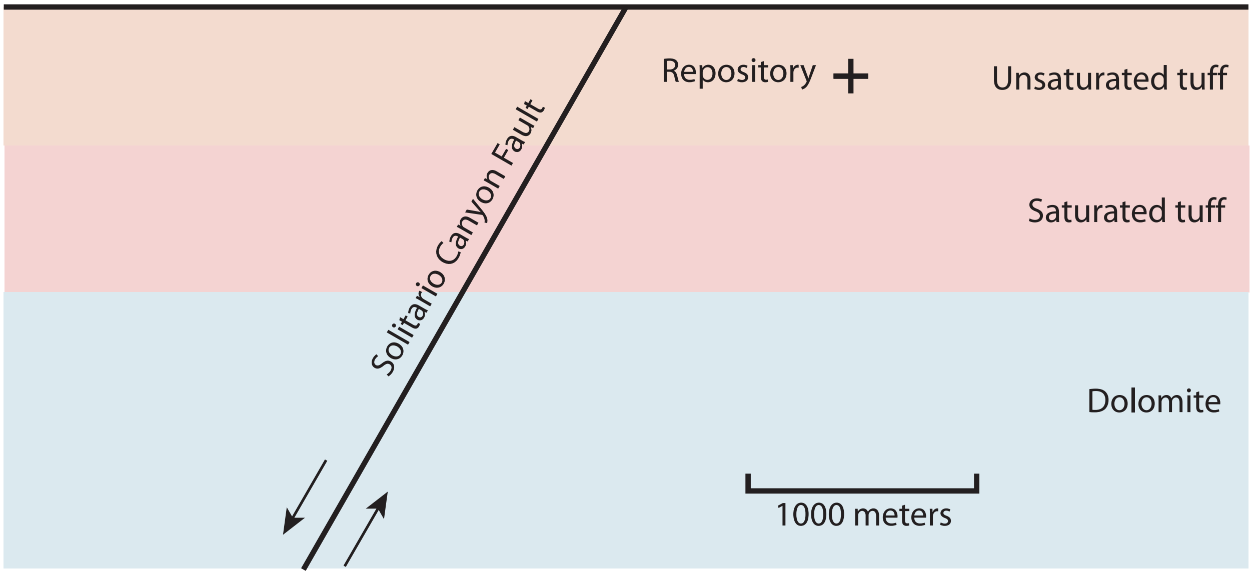


Figure 1. Demonstration 2D calculation of rupture on Solitario Canyon fault.

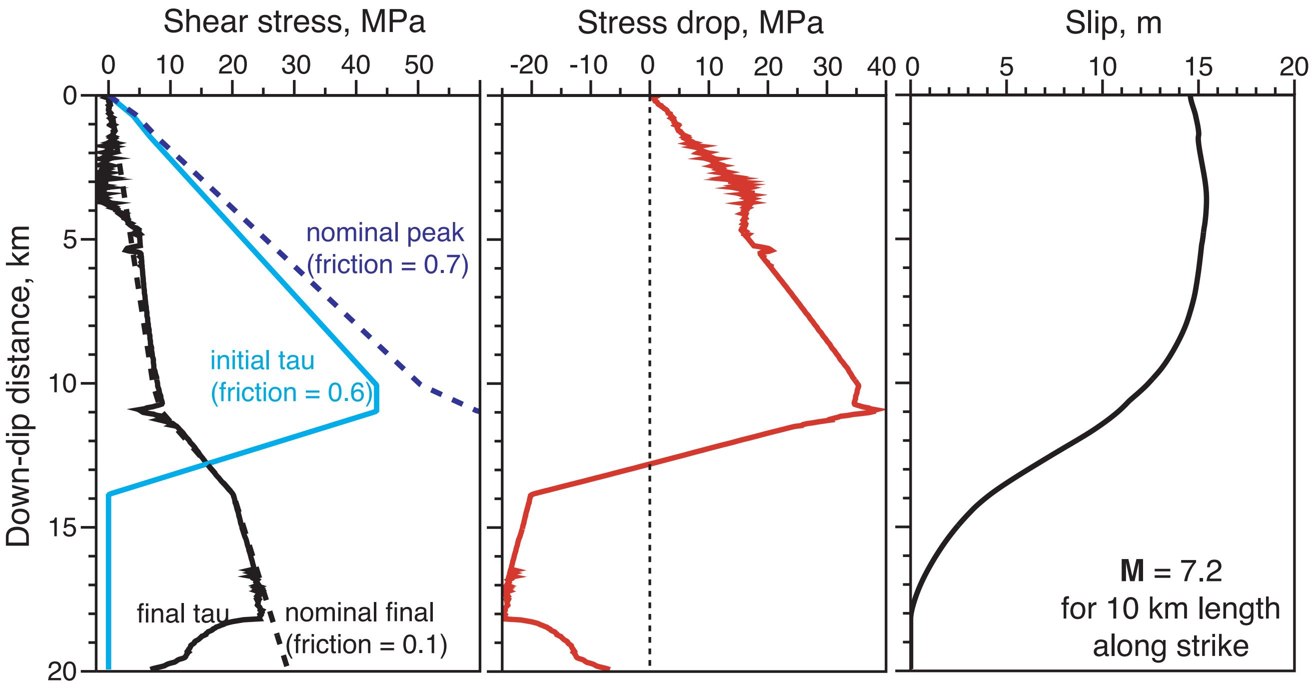
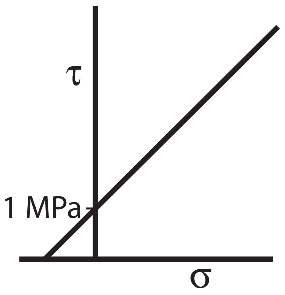


Figure 2. Modeled stress and slip on Solitario Canyon Fault in 2D plane strain.

Figure 3. Mohr-Coulomb yield condition.
Internal friction = 1.0,
angle of friction = 45 degrees,
cohesion = 1 MPa.



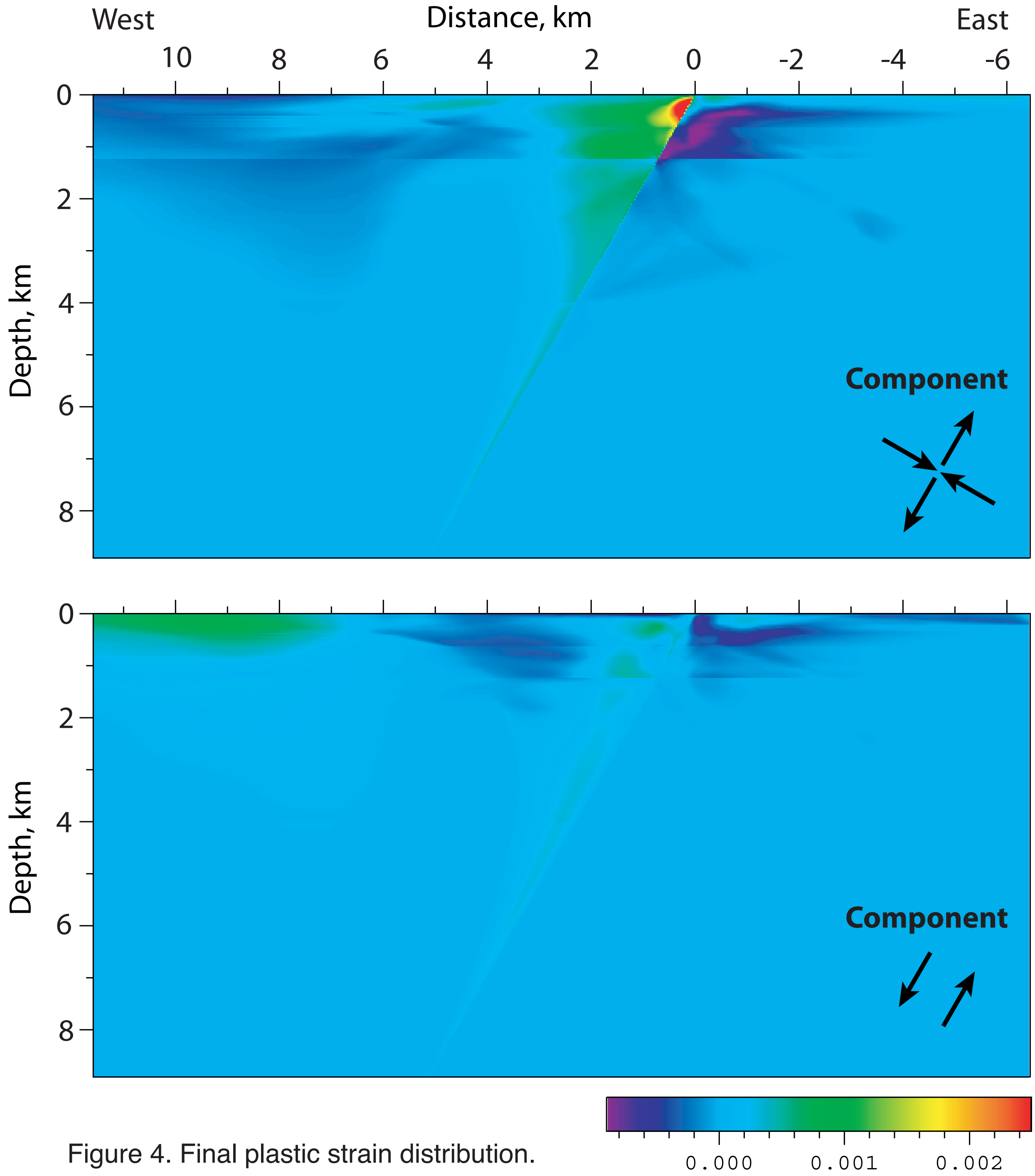


Figure 4. Final plastic strain distribution.

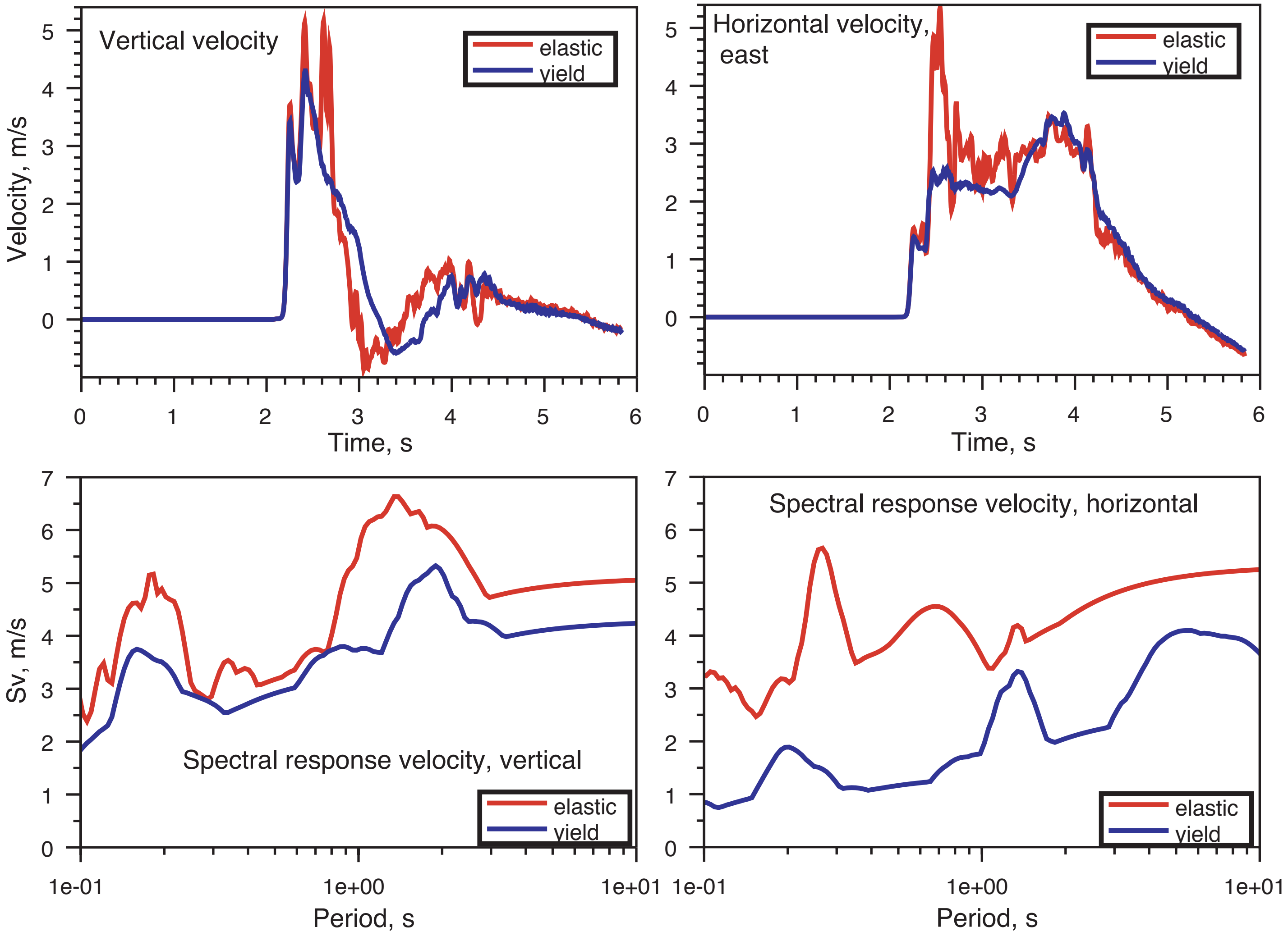


Figure 5. Comparison of velocity at repository site between the elastic calculation and the calculation with Coulomb yielding. Top: velocity; bottom: spectral response velocity; left: vertical component; right: horizontal east component.