2011 Annual SCEC report

Study of the origin of shallow slip deficit in strike-slip earthquakes through simulations of earthquake sequences in elasto-plastic media (PI: Kaneko)

Publications and abstracts resulted from this project:


Kaneko Y., Y. Fialko, D.T. Sandwell, X. Tong, and M. Furuya, Investigation of interseismic deformation along the central section of the North Anatolian fault (Turkey) using InSAR observations and earthquake-cycle simulations, SCEC Annual Meeting, 2011.

Kaneko Y., Y. Fialko, D.T. Sandwell, X. Tong, and M. Furuya, Investigation of interseismic deformation along the central section of the North Anatolian fault (Turkey) using InSAR observations and earthquake-cycle simulations, AGU Fall Meeting, T31E-08, 2011.

Y. Kaneko, Y. Fialko, X. Tong, D.T. Sandwell, and M. Furuya, Interseismic deformation and creeping along the central section of the North Anatolian fault (Turkey): InSAR observations and implications for rate-and-state friction properties, manuscript in preparation.

PI (Kaneko) presented the relevant results at seminars in several US universities:

- Seismology Seminar, UCLA, Los Angeles, CA, March 9, 2011.
- IGPP Seminar, UC Santa Cruz, Santa Cruz, CA, March 11, 2011.
- Seismolab Seminar, Caltech, Pasadena, CA, October 21, 2011.
- Geophysics Seminar, San Diego State University, San Diego, CA, November 8, 2011.
- Geophysics Seminar, University of Southern California, Los Angeles, CA, November 15, 2011.

Summary of research activities

Using simulations of spontaneous dynamic rupture with off-fault yielding, we have investigated whether the occurrence of inelastic deformation can account for shallow slip deficit inferred from slip inversions of several well-documented M7 earthquakes (Fig. 1). Our results suggest that shallow slip deficit due to coseismic inelastic deformation occurs under a wide range of parameters that characterize strength of the uppermost crust and can account for some, but not all of, the slip deficit inferred from kinematic inversions of geodetic data.

The goals of the project described in the 2011 proposal were:

- To estimate the amount of ‘artificial deficit’ in a geodetic inversion procedure that is based on a purely elastic model
- To quantify interseismic inelastic deformation and its contribution to coseismic shallow slip deficit
Figure 1: Distributions of coseismic slip for several ∼M7 strike-slip earthquakes averaged along the rupture length [Fialko et al., 2005, 2010]. These slip distributions were obtained from the inversions of near-field InSAR data or of a combination of InSAR and GPS data. The coseismic slip sharply decreases towards the Earth surface from a maximum value in the middle of the seismogenic zone.

We have accomplished the first goal discussed above and published the results in Geophysical Journal International [Kaneko and Fialko, 2011]. The results from the first part were also summarized in our 2010 SCEC annual report. Inelastic deformation in the shallow crust reduces coseismic strain near the fault, introducing an additional ‘artificial’ deficit of up to 10% of the maximum slip in inversions of geodetic data that are based on purely elastic models. The largest magnitude of slip deficit in our models combined with the bias in inversions accounts for up to 25% of shallow slip deficit, which is comparable to those inferred from kinematic inversions. We also show that unresolvable interseismic creep may account for some of the remaining discrepancy; this topic is discussed in more detail below.

Currently, we have been working on the second part: implementing off-fault plasticity into models of earthquake cycles, which is based on a numerical model published this year in Journal of Geophysical Research [Kaneko et al., 2011]. So far, we have been testing several implicit numerical algorithms for interseismic inelastic deformation.

**Shallow interseismic fault creep below detection limit**

For faults with low slip rates and large recurrence intervals such as those represented in Fig. 1, unresolvable shallow creep during the interseismic period may account for some of the inferred slip deficit. Since most geodetic measurements span only a few decades, interseismic creep rates smaller than ∼0.1 mm/yr may be unresolvable. One can estimate the contribution of potential interseismic creep to the overall slip budget. If we assume the fault slip rate of 1 mm/yr, the recurrence interval of ∼5000 years, and the surface creep rate of ∼0.1 mm/yr, the total shallow creep during the interseismic period is 0.5 m, accounting for up to ∼10% of the average coseismic slip (Fig. 1). While this effect alone is insufficient to explain the inferred coseismic slip deficit, the occurrence of such slow creep may increase the total amount of coseismic slip deficit in our elasto-plastic models.
Motivated by this argument, we further consider scenarios with a velocity-strengthening shallow layer that result in interseismic creep (Fig. 2a). To reproduce a fault with a low slip rate and a large recurrence interval, we assign a low loading rate $V_{pl} = 1 \text{ mm/yr}$ such that the resulting recurrence interval becomes 4800 years and the surface creep rate is $\approx 0.15 \text{ mm/yr}$ (Fig. 2a). As expected, the occurrence of interseismic creep increases the amount of coseismic slip deficit in the elastic simulation (Fig. 2b). The slip deficit in the elasto-plastic simulation in this case is 25% (Fig. 2b), larger than that in the case with a velocity-weakening shallow layer and with the same plasticity parameters. The difference in coseismic slip deficit between the elasto-plastic and elastic simulations is 10% (Fig. 2b). The results suggest that the occurrence of slow interseismic creep could account for some of the remaining discrepancy between shallow slip deficit predicted by our models and that inferred from inversions of geodetic data.

Study of interseismic deformation and shallow fault creep along the North Anatolian fault zone

Concurrently, we have also been working on a project related to the theme of the proposed work. More specifically, we have been investigating interseismic deformation along the central section of the North Anatolian fault (Turkey) using InSAR observations and earthquake-cycle simulations. The NAF is a major active right-lateral strike-slip fault in northern Anatolia and runs along the transform boundary between the Eurasian plate and the Anatolian plate (Fig. 3a). A sequence of eight $M \geq 7$ earthquakes ruptured $\sim 900 \text{ km}$ of the NAF from 1939 to 1999 [e.g., Sengör et al., 2005], posing significant earthquake hazard in Turkey. The NAF is similar to that of the San Andreas fault (SAF); they are matured strike-slip faults extending more than $\sim 1000 \text{ km}$. The long-term fault slip rate of the NAF is $22 \pm 3 \text{ mm/year}$ [e.g., McClusky et al., 2000], close to that of the southern
SAF [e.g., Fialko, 2006]. Measuring and modeling interseismic deformation and fault creep around the NAF will improve our understanding of both earthquake hazard and earthquake physics.

To infer interseismic deformation and potential fault creep, we use a space-based geodetic technique called Interferometric Synthetic Aperture Radar (InSAR) with 4 years of data collected by Advanced Land Observing Satellite (ALOS). We generated satellite line-of-sight (LOS) velocities for the three ascending ALOS tracks (603-605) covering the NAF between 31.2-33.2 degree East. LOS velocity maps for each track were obtained by averaging 15 to 30 radar interferograms spanning a time period of 4 years between 2007 and 2010 (Fig. 3b). We then modeled available InSAR and GPS data using numerical simulations of spontaneous earthquake sequences that incorporate laboratory-derived rate-and-state friction laws. Main findings were presented at 2011 SCEC Annual Meeting and 2011 AGU Fall Meeting, and are summarized below:

- Along the Ismetpasa section of the North Anatolian fault, our InSAR observations indicate surface creep at a rate up to 10 mm/yr (Fig. 3c); this is a large fraction of the inferred fault slip rate (20-25 mm/yr).
- The lateral extent of significant surface creep is about 75 km (Fig. 3c), broadly consistent with results of previous studies [Cakir et al., 2005] that used different radar data spanning different time periods.
- Neighboring fault sections do not exhibit shallow creep within the measurement accuracy (1-2 mm/yr).
- The inferred depth extent of shallow fault creep at Ismetpasa is 4-6 km (Fig. 3e).
- Dynamic models that incorporate rate-and-state friction combined with geodetic observations of interseismic deformation due to mature active faults can be used to infer in situ rate-state parameters of seismogenic crust (Figs. 3d,e).

Intellectual Merit:
One of the SCEC science objectives is to determine the origin, evolution and implications of on- and off-fault damage. Our research project has resulted in an improved understanding of how inelastic deformation (or off-fault damage) in the vicinity of active faults influences the coseismic slip distribution in large strike-slip earthquakes. The results have also impacted interpretations of fault slip based on geodetic data, as inversions of geodetic data based on purely elastic models may lead to an artificial slip deficit.

Broader Impacts:
Determining the origin of the shallow slip deficit is important for estimating seismic hazard, as suppression of shallow rupture could influence strong ground motion in the vicinity of active faults. Our project has linked advances in earthquake source physics, crustal deformation, earthquake geology, and computational science. Results from our research have been broadly disseminated through conference presentations, seminars, and publications in peer-reviewed literature.
References


Figure 3: (a) Map of Turkey and the surrounding areas. The North Anatolian fault (NAF) extends westward from a junction with the East Anatolian fault at the Karliova Triple junction in eastern Turkey, across northern Turkey and into the Aegean Sea. Our focus region is indicated by a rectangle. (b) Line-of-sight (LOS) velocity of the Earth’s surface from a stack of ALOS radar interferograms spanning a time interval between 2007 and 2010. Arrow shows the radar look direction, and LOS velocities away from the satellite are assumed to be positive. (c) Inferred shallow fault creep near the Ismetpasa segment from three neighboring tracks 603-605. (d) Surface velocities near the locked segment from InSAR data shown in panel c and those computed from simulated interseismic deformation in a 2-D model of earthquake cycles. The inset shows the depth-variable distribution of rate-and-state parameters \((a - b)\) assumed in this model. Since the last major earthquake in this segment occurred in 1944, we compare InSAR surface velocities with the simulated interseismic deformation at 65 years after the previous event. (e) Surface velocities near the locked segment from InSAR data and those computed from simulated interseismic deformation in a 2-D model of earthquake cycles. Since the last major earthquake in this segment occurred in 1951, we compare the InSAR data with the simulated interseismic deformation at 55 years after the previous event.