Introduction

The three-dimensional configuration of active faulting in the Puente Hills region is partly constrained by seismic reflection, well control, seismicity locations and predictions of fault geometry using kinematic fault-related fold theory [Shaw and Shearer, 1999; Shaw and others, in review], however critical elements of the fault system remain unresolved. For example, multiple fault configurations can match the indirect seismic and fold observations and the nature of intersections of the Puente Hills thrust faults and the Whittier faults are unresolved. In order to validate the proposed fault models of the Puente Hills region, continuum mechanics models simulate deformation associated with alternative probable fault configurations and evaluate slip rates as well as mechanical efficiency of the fault system and secondary faulting. The project has constrained the set of plausible fault models by: 1) comparing slip rates from the three-dimensional model of interacting faults with available paleoseismic data and kinematic inferences; 2) analyzing the distribution of work within the fault system models, with the assumption that the most mechanically efficient model is potentially the most physically realistic and 3) identifying regions that are close to failure that may contain additional unrecognized faults. The most viable fault configuration is that which produces the best match to observations of slip-rate and may be that with the lowest mechanical efficiency. Additionally, the best fitting model can provide slip rate estimates on fault segments for which slip rates are currently unconstrained (e.g Montebello fault and strike-slip along Puente Hills thrusts).

The Fault Model and Continuum Mechanics Tool

A detailed three-dimensional model of the fault configuration of the Puente Hills structures has been constructed (Fig. 1) based on seismic reflection data, well control, relocated seismicity and predictions of fault geometry using kinematic fault-related fold theory and associated growth strata [Shaw and Shearer, 1999; Oskin et al. 2000; Shaw and others, in review]. The fault model of the Puente Hills and the Los Angeles basin can be viewed in three-dimensions at our
The boundary element method (BEM) numerical code Poly3D [Thomas, 1994] is used to assess the response of this fault model under geodetically determined horizontal contraction [e.g. Fiegl and others, 1993] in order to simulate present-day contraction in the eastern Los Angeles Basin. BEM is a numerical technique for solving the governing differential equations of continuum mechanics. In principle, this method can describe the deformation of any solid body if either the tractions or displacements are prescribed along the internal and external boundaries of that body. The stress, strain, and displacement fields throughout the body are uniquely determined by these boundary conditions. The three-dimensional BEM tool Poly3D discretizes 3D faults into 2D polygons, which have constant displacement discontinuity [Thomas, 1994]. Such discretization permits ready implementation of the Community Fault Model products (T-surf) to simulate complex and intersecting fault surfaces. Poly3D is used to investigate three-dimensional interaction of infinitely weak faults within an isotropic, homogeneous and elastic half-space.

**Methodology for creating viable fault models using CFM products**

Over the past several years Cooke and students have been honing a three-dimensional model of faulting in the Los Angeles Basin. The complex nature of subsurface faults in this region challenges the numerical stability of fault solutions. Although the BEM models have great benefit over FEM models because they need only discretize the fault surface rather than the entire volume, intersecting elements and non-coincident nodes (vertices) can produce instabilities. Over the past year Cooke and Griffith, with assistance from UMass undergraduate Kathy Staffier, eliminated the existing irregularities in the fault model, developed a procedure for processing CFM products to avoid fault mesh irregularities and developed guidelines for detecting and remedying problems within the fault mesh. To further enhance the numerical stability of the BEM solutions, uniform element size is maintained. This necessitates the coarsening of some CFM fault meshes, another procedure honed in the past year. The current generation of fault solutions produced by Cooke and Griffith are numerically stable and, aside from some fault surface coarsening, reflect the SCEC community’s current understanding of three-dimensional faulting in the Los Angeles basin.

**Fault Intersection Geometry**

Four intersections for strike-slip and thrust fault systems [Rivero and Shaw, 2000] are kinematically viable for the intersection of the Puente Hills and Whittier faults. Because the Whittier fault predates the development of the PHT we do not expect the Whittier fault to offset the Puente Hills system; therefore the Coyote Hills segment either abut against (model A) or offset the Whittier fault (Model B). A third model, C, renders the portion of Whittier below the Coyote Hills inactive. Mechanical models assess the sensitivity of slip patterns to these different intersection geometries (Fig. 2). The dip slip along the PHT fault segments are compared to kinematically inferences by Shaw and co-workers from shallow seismic images of growth strata associated with these fault tips [Shaw and others, in review]. Because changes in material rheology, fault constitutive properties and remote strain rate may alter the magnitude of slip rate, we are primarily concerned with approximating the dip slip rates and correlating the distribution of slip long the fault segments rather than matching rates exactly. The model with Coyote Hills extending to 20 km depth has closer match of dip slip rate because the longer length of this fault yields greater slip (Fig. 2). This result suggests that
models B and C are preferred over A and that the Coyote Hills fault does not abut the Whittier fault.

The dip slip rate in models B and C is similar for all segments of the PHT. However, the kinematically inferred rates show significantly greater slip rate along the Coyote Hills segment than the adjacent Los Angeles and Sante Fe segments. This increase in slip rate from Santa Fe to Coyote Hills cannot be explained by changes in fault orientation relative to remote contraction or by interaction with the Whittier fault. The dip-slip rates along the modeled Los Angeles and Sante Fe Springs segments are closer to the kinematically inferred rates than the Coyote Hills segment. The discrepancy between the mechanical results and kinematic inferences for slip slip on Coyote Hills requires investigation of alternative fault configurations and should be explored further.

The right-lateral strike slip rate along the Whittier fault from paleoseismic data is 1-3 mm/yr [Gath et al, 1992]. The model B with Coyote Hills crossing and offsetting the Whittier fault has slip rates closest to the paleoseismic rates (Table 1). These results further suggest that the Coyote Hills fault does not abut Whittier. Furthermore the closer match of model B over model C suggests that the active Whittier fault extends to the base of the seismogenic zone.

Table 1: Model results

<table>
<thead>
<tr>
<th>Model</th>
<th>Whittier average strike slip</th>
<th>Average strain energy density</th>
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</thead>
<tbody>
<tr>
<td>Model A</td>
<td>0.52 ± 0.31</td>
<td>0.00915</td>
</tr>
<tr>
<td>Model B</td>
<td>1.01 ± 0.32</td>
<td>0.00883</td>
</tr>
<tr>
<td>Model C</td>
<td>0.93 ± 0.30</td>
<td>0.00907</td>
</tr>
</tbody>
</table>

Within the mechanical models, strike slip along the PHT segments is < 0.15 mm/year. This suggests that primarily thrust earthquake events are expected along these faults and the hazard of strike-slip events has not been underestimated.

**Mechanical Efficiency**

The mechanical efficiency of each model with differing intersection geometry provides another means to discern between alternative models that match paleoseismic observations. Mechanical efficiency measures the degree to which strain is partitioned into fault slip rather than elastic strain of the host rock [Cooke and Kameda, 2002]. Mechanically efficient fault systems are those that deform by slip along existing faults rather than straining the host rock, which might fail yielding new fault surfaces. Geologic and laboratory observations of fault systems support the premise that fault systems evolve towards greater mechanical efficiency [Scholz, 1990].

The global mechanical efficiency of three-dimensional fault systems can be assessed by the average work done within the host rock or average strain energy density (SED) [Timoshenko and Goodier, 1934; Cooke and Kameda, 2002]. This work measures the amount of elastic strain energy stored at any point within the host rock. SED concentrations may arise in locally deformed regions, such around fault tips and SED shadows may develop adjacent to slipping faults where the elastic strain within the rock has been lessened. To quantify the overall SED of the entire fault system, we calculate the average SED throughout each of the models. The model of Coyote Hills offsetting the Whittier Fault has the greatest mechanical efficiency as indicated by the lowest average SED (table 1). Thus, the model with best-fit to independently determined slip rates also has the greatest mechanical efficiency. This correlation further supports the preference of
model C and also supports the use of average SED in future fault geometry validation studies. Because SED is easy to calculate and represents the overall behavior of the fault system it can be a powerful diagnostic tool.

Secondary Faulting

A geometric view of fault systems supposes that under the same tectonic strain greater fault surface area results in less slip along each individual fault segment, however mechanical models show a more nuanced relationship between fault surface area and slip rate. Our results demonstrate that stored strain (ie. SED) also drives fault slip. We explore this by adding faults to the basic model containing just PHT and Whiter faults.

First the Montebello fault is added to hanging wall of the Santa Fe fault. The Montebello fault east of the Whittier fault underlies an anticlinal fold, which suggesting that significant contraction may be accommodated along this structure (Fig. 3).

Addition of the Montebello fault does not change slip distribution on the nearby Santa Fe Springs segment even though the Montebello fault accommodates significant dip slip, average dip-slip rate ~0.15 mm/yr. Because the Montebello fault is added to the model within a region of high SED, the slip of Montebello draws from the stored elastic strain in the hangingwall of the Santa Fe Springs segment rather than decreasing slip on Santa Fe (Fig. 3).

Second, we add the nearby major fault of the Los Angeles basin to the basic PHT and Whittier model. When these faults are added to the model, slip rate on the Los Angeles fault decreases dramatically (Fig. 3). Several major faults (e.g. Lower and Upper Elysian Park, Raymond) were added near the Los Angeles segment in areas of low SED (Fig. 3). In contrast to the addition of the Montebello fault, the slip on these major faults could not draw from stored elastic strain and instead lowered slip along the PHT.

These results suggest that adding faults to regions of high SED has less influence on slip than adding faults to regions of low SED. Thus, a model that matches slip rates to paleoseismic rates may still omit significant faults that lie in regions of high stored strain. These conclusions will greatly aid future efforts to validate CFM fault geometries.

References


Inferred from kinkband width with 27° dip

Figure 2. Dip-slip rate across the PHT using three intersection geometries between the Coyote Hills fault (CH) and Whittier fault. Los Angeles fault (LA) and Santa Fe Springs fault (SFS) are unchanged in each model. Red triangles represent model with Coyote Hills abutting Whittier at 7 km. In the Blue circles represent Coyote Hills fault extending to 20 km depth and offsetting Whittier fault. Green circles represent Coyote Hills extending to 20 km depth with Whittier inactive below Coyote Hills fault. Intersection geometry illustrations are modified from Rivero and Shaw (2000).

Figure 3. A) and B) SED along two slices through model of PHT and Whittier. Contour shows average SED. Locations of Raymond (RF), Upper Elysian Park (UEP), Lower Elysian Park (LEP), Newport-Inglewood (NI), Montebello (MF), Los Angeles segment (LA), and Santa Fe Springs segment (SFS) illustrated. C) Dip-slip distribution across PHT for the basic (PHT & Whittier) model and models with Montebello and adjacent faults added.