2012 SCEC Annual Report

Reexamining the effects of material heterogeneity on the slip distribution of the 1994 Northridge earthquake

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Summary

The major goal of this ongoing research is to build a modeling framework integrating three-dimensional heterogeneity in material properties that may be used to interpret quasi-static geodetic observations of earthquake cycle deformation.

A Smith College engineering sophomore, Bismita Sahu, spent summer 2012 working on the elastic dislocation modeling. She had some background in mechanics and computer programming before beginning the work and learned Matlab programming and inverse theory in the process. She carried out initial elastic dislocation modeling of the earthquake that placed constraints on the feasibility of inferring details of the coseismic slip given the GPS data distribution.

We estimated coseismic slip distributions on a Community Fault Model-based, non-planar representation of the Northridge source fault within a homogeneous elastic half-space and layered elastic space but found that neither model provides a satisfactory fit to the data. We used an adaptive fault remeshing routine to find element sizes and smoothing constraints that are appropriate for the data distribution and modeling framework.

We generated an initial catalog of Green's functions based on the static offsets predicted by SPECFEM3D simulations of earthquake sources located on the Northridge source fault. Most importantly, we established the machinery for calculating static offsets due to unit strike-slip and dip-slip on geometrically complicated surfaces, recognizing the vast computational expense. Additional benchmarking will allow us to use these Green's functions to assess the impact of three-dimensional structure on the estimate of coseismic slip, augmenting the comparison we made between models based on dislocations embedded in homogeneous and one-dimensional layered elastic spaces.

Our overarching goal is a publicly available catalog of Green's functions generated with SPECFEM3D that integrates several SCEC initiatives. The Community Fault Model will serve as the source geometry on which interseismic slip deficit and coseismic slip occur. Seismic wave propagation through the crust with properties as represented in the Community Velocity Model is simulated using SPECFEM3D. Static displacements due to unit slip on CFM sources are predicted at GPS stations of the Community Motion Model, providing a full suite of Green's functions to be used by the crustal deformation modeling community. We envision this product being made available first for the Northridge source fault, our test case, but eventually for all structures within the CFM, allowing the Green's functions to be implemented in estimating the distribution coseismic slip of future earthquakes and of ongoing earthquake cycle processes throughout southern California.

Technical Report

Introduction

The work we carried out under this proposal provided us with important lessons for moving forward toward the primary scientific goal of assessing the impact of three-dimensional material property variations on estimates of earthquake cycle slip distributions. By continuing our work with benchmarking the synthetic static offsets calculated using SPECFEM3D against analytical dislocation solutions, we developed a better appreciation for the demands of this type of problem, both in terms of time investment and computational costs. Overall, we are encouraged by our preliminary results and will continue this work, focused first on refining the Northridge earthquake test scenario and then moving on to considering the effects of material heterogeneity on coseismic slip distributions and interseismic fault slip deficit rates throughout southern California, and eventually wherever high quality geodetic data and crustal models are available. We are confident that refinement of our workflow will allow this type of analysis to become a tool used regularly in using geodetic observations to constrain earthquake cycle processes in the presence of three-dimensional crustal heterogeneity.

We chose the 1994 M_W=6.7 Northridge earthquake as a target example for exploring the effects of material property variations on the estimated slip distribution because of its occurrence in a region of substantial crustal heterogeneity (the Los Angeles Basin) and availability of coseismic GPS displacements [*Hudnut et al.*, 1994; *Shen et al.*, 1996]. Previous studies examined the impact of variation in material properties on estimation of coseismic slip [e.g., *D J Wald and Graves*, 2001] but did not formally compare slip distributions estimated using homogeneous and 3-D crustal models. Our ongoing research is moving toward comparison of inversions of geodetic data for the coseismic slip distribution on the Northridge source fault, based on its representation in the Community Fault Model [*Plesch et al.*, 2007], embedded in (1) a homogeneous elastic half-space, (2) a layered elastic space, and (3) a three-dimensional crustal structure from the Harvard Community Velocity Model [CVM-H 11.9; *Süss and Shaw*, 2003; *Plesch et al.*, 2011], which includes contributions from recent adjoint tomography studies [*Tape et al.*, 2009; *Tape et al.*, 2010]. For (1), we calculate Green's functions relating displacement at GPS stations to slip on triangular dislocation elements (TDEs) representing the fault surface using the algorithms of *Meade* [2007]. For (2), we calculate Green's functions using the layered elastic dislocation code of *Wang et al*. [2003], using point sources at TDE centroids to approximate the Northridge fault geometry. For (3), we use the spectral finite element wave propagation code SPECFEM3D [*Komatitsch et al.*, 2004] to calculate synthetic displacement seismograms at GPS station locations. We use the three-component static offsets from these seismograms, after passage of the dynamic wave field, as our set of Green's functions.

Dislocation-based estimates of Northridge coseismic slip

Given the computational expense of SPECFEM3D simulations, we worked on degrading the CFM representation of the Northridge source fault, reducing the mesh from 5995 elements to 50–100 elements. We carried out this remeshing using several methods. First, the original source fault was remeshed by Andreas Plesch using GOCAD. Using this 94-element representation, we explored the similarity between the surface displacement field given by slip on these elements and various point source representations of the geometry. We remeshed the 94-element fault into 897 elements by simply subdividing each of the 94 TDEs into smaller triangles but maintaining each parent element's geometry. We calculated surface displacements at Northridge GPS station locations due to unit strike and dip slip on each element using the exact analytical expressions of *Meade* [2007] and compared these displacements to equivalent calculations [*Okada*, 1985; *Wang et al.*, 2003] for point sources placed at the element centroids. The results indicate that a) for a coarse discretization of the fault geometry, surface displacement due to moment at a single point source at the centroid of a TDE provides a good approximation for displacement due to slip on the TDE (Figure 1a, b), and b) differences up to 35% exist between surface displacement predicted by point sources embedded within a homogenous elastic half-space and a one-dimensional layered space (Figure 1c). Both of these results are promising for future SPECFEM simulations: the relatively coarse permissible parametrization of the fault lowers the required computational expense of the simulations, and the substantial differences between the homogeneous and layered spaces provides additional impetus for considering three-dimensional crustal structure in the inversions.

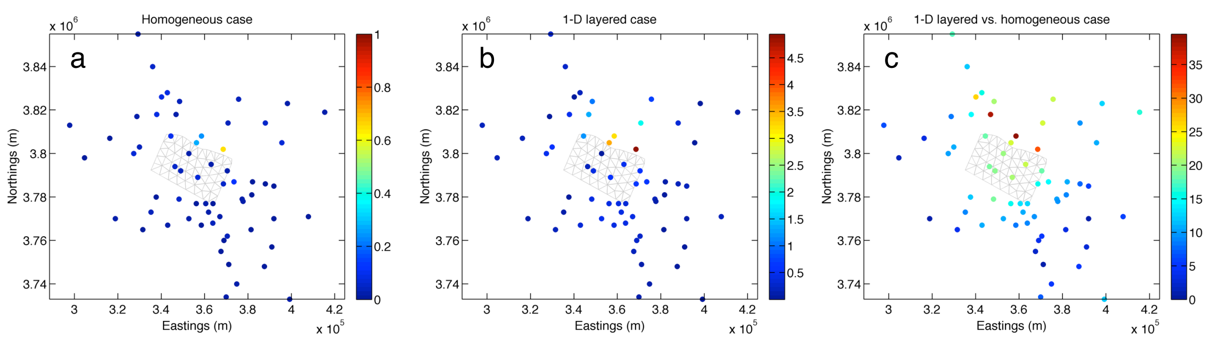

Figure 1. Comparison of surface displacement magnitude from different parametrizations of the Northridge source fault. The colors for all panels show the percent difference between the displacement magnitude at Northridge stations calculated using a reference model and a comparison model. For a), the reference model represents predicted surface displacements from 94 triangular dislocation elements representing the source fault, and the comparison model is the displacement from point sources located at each element centroid. For b), the reference model is 897 point sources, representing a densified version of the 94 element mesh, and the comparison model is the 94 point source representation. Both are embedded within a 1-D layered space [Wald et al., 1995]. For c), the reference model is the homogeneous TDE model and the comparison model is the 1-D layered, 94 point source model.

We further modify the mesh using the "DistMesh" [*Persson and Strang*, 2004] and "MESH2D" [*Engwirda*, 2005] algorithms for Matlab, both available on the Mathworks File Exchange. To guide mesh refinement, we use automated fault discretization tools that use the data and model resolution matrices to determine optimal element size and Laplacian smoothing constraints [*Barnhart and Lohman*, 2010]. We modified these algorithms to carry out the automated mesh refinement based on a nonplanar fault, interpolating the nodal coordinates of adaptively remeshed TDEs based on the high-resolution CFM-based Northridge source fault. Furthermore, we used the lessons of our point source approximation tests to implement a version of the mesh refinement that relies on the *Wang et al*. [2003] layered Green's functions, permitting automated fault geometry refinement in a one-dimensional elastic layered space. The results of these tests find that slip (up to 2.5 m; Figure 2a) estimated on the fault in homogeneous elastic half-space is shallower and lower magnitude than that estimated in a layered space (up to 4 m; Figure 2b). However, neither model produces a good fit to the data. The homogeneous model gives a mean residual displacement magnitude of 26.5 mm (compared to a mean observed displacement magnitude of 48.1 mm), with only 30% of displacement components fit to within their reported uncertainty. The one-dimensional model features a mean residual displacement of 38.2 mm, with just 23% of residual displacement components less than the uncertainty.

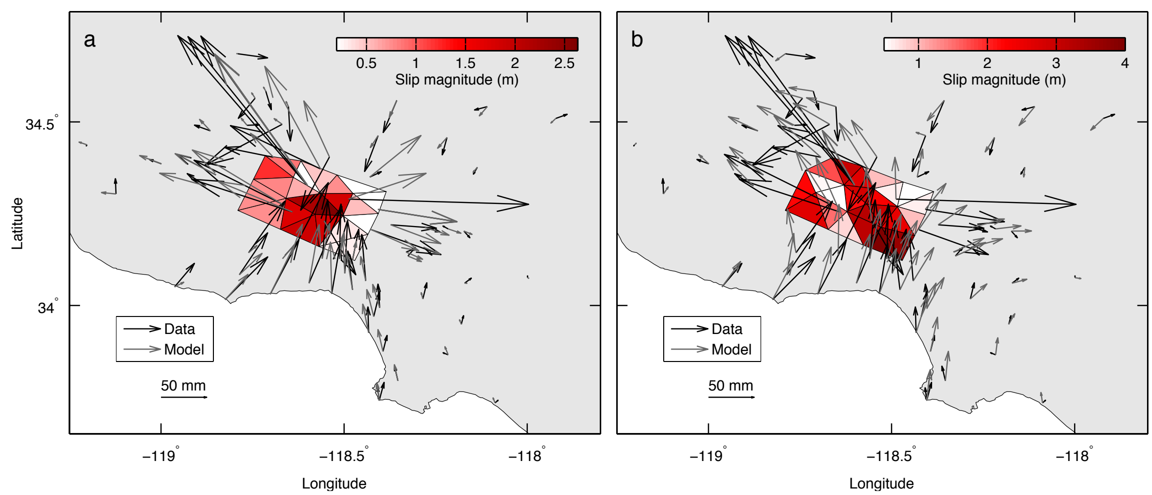

Figure 2. Estimates of Northridge coseismic slip distribution on dislocations embedded in a) a homogeneous elastic half-space and b) the one-dimensional layered model of *Wald et al*. [1995]. In both cases, a non-planar, CMF-based representation of the Northridge source fault was automatically remeshed based on data and model resolution [*Barnhart and Lohman*, 2010]. For a, the analytical expressions of *Meade* [2007] were used to calculated Green's functions relating slip to surface displacement. For b, point sources were placed at the element centroids, and Green's functions were calculated using the layered dislocation code EDCMP [*Wang et al*., 2003]. Estimated peak slip is greater in magnitude and deeper in location in the layered case than in the homogeneous case. Differences in the mesh geometry arise from differences in the Green's functions, which contribute to the adaptive remeshing procedure.

3D models and meshes for wavefield simulations

All synthetic seismograms were computed using SPECFEM3D, which employs a spectral-element method to solve the wave equation [*Komatitsch et al.*, 2004]. SPECFEM3D uses unstructured hexahedral meshes, which we generated using GEOCUBIT [*Casarotti et al.*, 2008]. We created six meshes for three different models: homogeneous, layered, and CVM-H 11.9 (including topography). For each of these models we constructed a coarse and a fine mesh, which allowed us to quantify the numerical resolution associated with the coarse mesh. This procedure is discussed in detail in the 2013 SCEC report by Tape ("Toward iterative improvement of CVM-H 11.9 using spectral-element and adjoint methods").

Our initial effort, still on-going, is to benchmark the static offsets computed from wavefield simulations with analytical solutions. Our preliminary results were presented in *Tape et al*. [2011], where we showed good agreement for the homogeneous and 1D models. In each of our simulations we save the displacement time series at 576 stations representing three groups: (1) a uniform grid of 357 stations, (2) a dense uniform grid in the center, and (3) the GPS station locations that recorded the 1994 Northridge earthquake. For our benchmark tests, we place a strike-slip earthquake (point source or finite source) at the center of the simulation volume (e.g., Figure 3). The dense grid allows us to capture the near-source variations in the displacement field.

Green's function database

We have undertaken the first major step by computing a database of Green's functions for a 58-patch parameterization of the Northridge fault. The computation associated with the database is (58 patches) × (2 mechanisms) × (96 cores) × (32 minutes) ≈ 6000 CPU-hours.

These simulations were performed on the Arctic Region Supercomputer Center at U. Alaska Fairbanks. In this case, the structural model was the 1D layered model, and the 3D model will require a factor of at least 4 more in computational cost. The computational machinery for performing simulations and processing seismograms has now been established.

Here we outline our procedure for constructing the Green's function database. The Northridge fault is parameterized into N patches, where higher N results in a surface that deviates the least from the original surface provided by the Community Fault Model, yet may not be warranted by the geodetic data distribution for the Northridge case. Hence, we initially choose a coarse parameterization of the fault. For each patch, we compute dip-slip and strike-slip moment tensors, located at the centroid, and simulate wave propagation due to each source (Figure 3).

The synthetic seismograms show the dynamic wavefield followed by an obvious static offset. Although for our purposes we are only interested in the static offset, it is clear that the database offers the potential for simultaneous inversion of the dynamic wavefield as well. In Figure 3, we show the static displacement field associated with one of the moment tensors. Following the analysis in *Tape et al*. [2011], we will first validate these displacement fields with analytical solutions. Then we will be in position to compute the database for CVM-H 11.9 to address the ultimate goal of testing whether the 3D structure (with topography)—as meshed at a

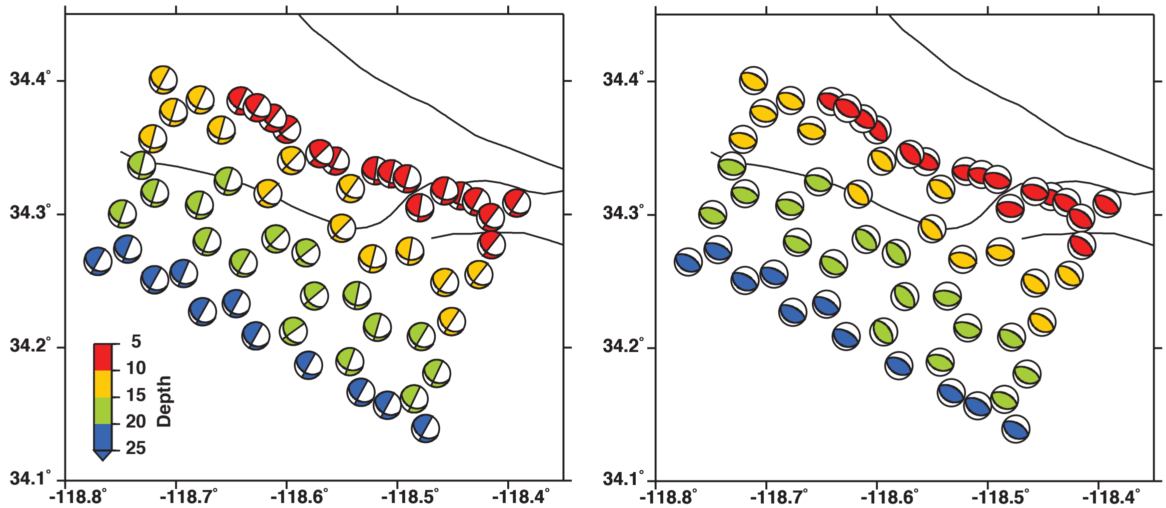

Figure 3. Moment tensors equivalent to unit strike (left) and dip (right) slip at the centroids of the 58 elements representing the Northridge source fault. Each earthquake source is used as input into SPECFEM3D, giving the catalog of Green's functions relating fault slip to surface displacement via wave propagation through the CVM-H.

particular numerical resolution—will have a significant impact on the estimation of source parameters for the Northridge earthquake as compared to the homogeneous and 1D layered cases.

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Intellectual merit

Our overarching goal is a publicly available catalog of Green's functions generated with SPECFEM3D that integrates several SCEC initiatives. The Community Fault Model will serve as the source geometry on which interseismic slip deficit and coseismic slip occur. Seismic wave propagation through the crust with properties as represented in the Community Velocity Model is simulated using SPECFEM3D. Static displacements due to unit slip on CFM sources are predicted at GPS stations of the Community Motion Model, providing a full suite of Green's functions to be used by the crustal deformation modeling community. We envision this product being made available first for the Northridge source fault, our test case, but eventually for all structures within the CFM, allowing the Green's functions to be implemented in estimating the distribution coseismic slip of future earthquakes and of ongoing earthquake cycle processes throughout southern California.

Broader impacts

This project funded a summer research fellowship for Bismita Sahu, a current Smith College junior engineering major. The research gave her experience in Matlab programming, inverse theory, and earth science, allowing her to see connections between her engineering coursework and a natural application.