

## Final Project Summary — PEER Lifelines Program

<b>Project Title—ID Number</b>	<i>Seismic Moment Tensors and Finite-Source Analysis of Chi-Chi Aftershocks—1E06</i>		
<b>Start/End Dates</b>	1/1/02 – 12/31/02	<b>Budget/ Funding Source</b>	\$44,899 / PG&E/CEC
<b>Project Leader (boldface) and Other Team Members</b>	<b>Dreger (UCB), Chi (UCB), Rhie (UCB)</b>		

### 1. Project goals and objectives

The objective of this project was to estimate the earthquake source parameters for aftershocks of the Chi-Chi earthquake and other Taiwanese events for use by researchers participating in the Next Generation Attenuation (NGA) project. Revised locations, style of faulting from first motion focal mechanisms and seismic moment tensors, moment magnitude and finite-source parameters such as the distribution of fault slip are necessary parameters for the development of new strong motion attenuation relationships. The finite-source parameters are of particular importance since they allow the determination of the distance to the closest point of the fault with appreciable slip rather than simply the distance to an epicenter, assumed fault plane, or the surface projection of the fault.

### 2. Benefits of the results of this project to develop technologies and protocols to mitigate the vulnerability of electric systems and other lifelines to damage directly and indirectly caused by earthquakes. Also, benefits to develop assessment techniques to evaluate damage to electric systems caused by earthquakes and to assess fiscal impacts due to the loss of electric service to the community.

The 1999 Chi-Chi, Taiwan earthquake sequence produced the most complete strong motion data set to date with observations ranging from 100s of meters from the fault to 100s of kilometers. Strong motion data was obtained for the Mw7.6 mainshock and numerous large Mw>6 aftershocks. This data set will contribute significantly to the revision of existing attenuation relationships and the development of new relationships that take additional source information into account, such as directivity, which is one objective of the Next Generation Attenuation (NGA) relationship project. The results of this project provide the necessary information for using Chi-Chi aftershocks to update these relationships.

### 3. Brief description of the accomplishments of the project

Strong motion data for 30 aftershocks of the September 1999 Chi-Chi, Taiwan earthquake sequence, compiled by PEER Lifelines, were investigated to determine seismic moment tensors, finite-source models, and to evaluate event locations. This data set provided by the Taiwan Central Weather Bureau consisted of strong motion accelerograms from 30 aftershocks with local magnitudes ( $M_L$ ) between 4 to 6.8. Finite-source parameters were obtained for 6 of the large ( $M_6+$ ) aftershocks, seismic moment tensors for 4 of the  $M_5+$  aftershocks, and style of faulting information for 15 of the aftershocks. A relationship between the reported local magnitude and moment magnitude was determined. Analysis of event locations using both P and S-wave picks and a grid search routine indicates that the locations provided with the data set are adequate for NGA purposes.

For each of the 6  $M_6+$  aftershocks approximately 1000 inversions were performed to determine the orientation of the rupture plane, as well as the rupture velocity, dislocation rise time, and hypocenter location parameters. The resulting slip models have been delivered to Brian Chiou and can be obtained from; [http://www.seismo.berkeley.edu/~dreger/peer\\_chichiaftershocks.zip](http://www.seismo.berkeley.edu/~dreger/peer_chichiaftershocks.zip).

Figure 1 gives an example of the sensitivity analysis for fault orientation and rupture velocity, and Figure 2 shows the best fitting slip distribution for one of the events. The obtained slip models may be used to estimate the distance of strong motion stations to the closest point of the fault that actually slipped during

the earthquake. In the particular example (Figure 2) the approximately 15 km by 5 km slip patch extending updip and to the south of the hypocenter is interpreted as the ruptured fault area.

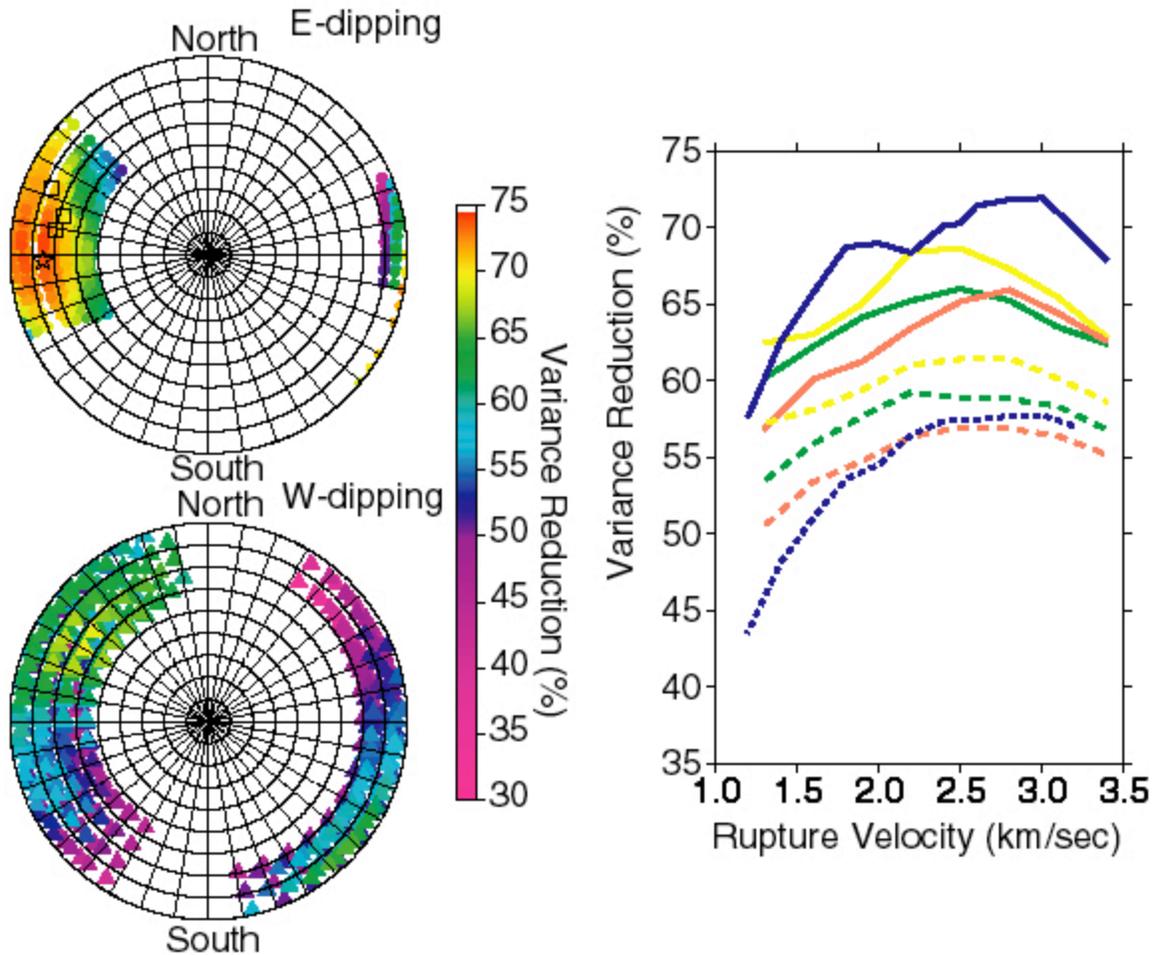


Figure 1. The left shows P-axes for east-dipping (top) and west-dipping (bottom) planes for the M6.3 aftershock on 1999/09/25. Each symbol represents a finite-source inversion. The color is scaled to a measure of fit to the seismic velocity waveforms in the 0.02 to 0.5 Hz passband. The sensitivity analysis shows clearly that the east-dipping plane provides a superior fit to the data, and gives an idea of the uncertainty in the fault orientation. On the right several east-dipping (solid lines) and west-dipping (dashed lines) fault orientations are examined in terms of the rupture velocity. The best solution obtained shows that the rupture velocity of 3 km/s is well constrained.

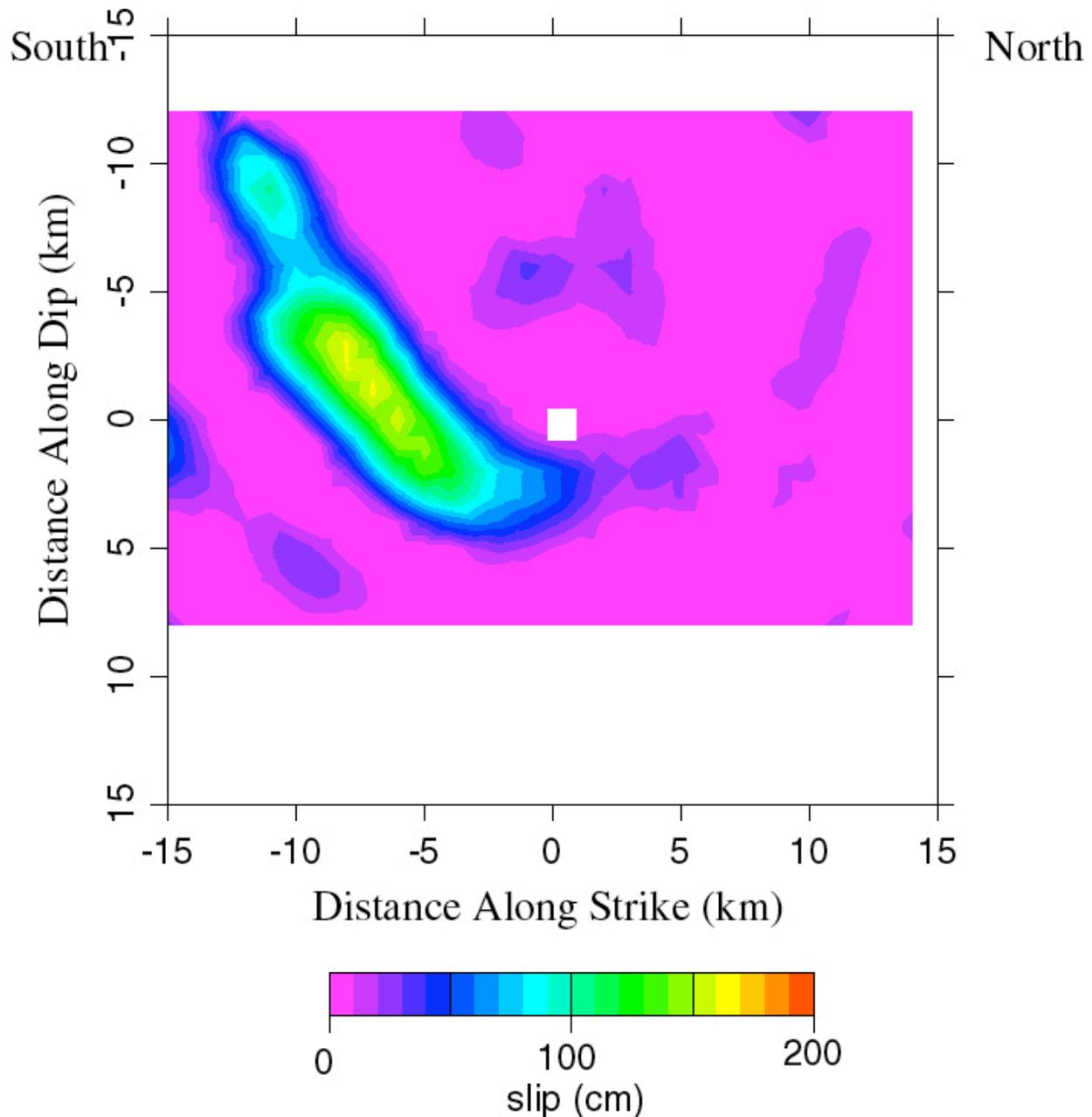


Figure 2. Slip distribution for the the M6.3 aftershock on 1999/09/25. The hypocenter is shown as a square and is at a depth of 16 km. The fault is oriented with a strike of 5 degrees, a dip of 30 degrees to the east and a slip-vector (rake) of 100 degrees.

Beyond the practical objectives of this study the results also contribute to improved understanding of the fault network in central Taiwan including segmentation of the Chelungpu fault zone, the orientation of ancillary faults and the style of the collisional tectonics.

Two peer-reviewed publications and a Ph.D. thesis resulted from this study:

- Chi, W-C, and D. Dreger (2004). Finite fault inversion of the September 25, 1999 (Mw6.4) Taiwan earthquake: Implications for GPS displacements of the Chi-Chi, Taiwan sequence, *Geophys. Res. Lett.*, 29(14), 1694, doi:10.1029/2002GL015237.

- Chi, W-C (2003). From subduction to collision: Results from seismic profiling, gravity modeling, and earthquake finite-fault inversions in the Taiwan region, Ph. D. thesis, University of California, Berkeley, 200p.
- Chi, W-C, and D. Dreger (2004). Crustal deformation in Taiwan: Results from finite source inversions of six Mw>5.8 Chi-Chi aftershocks, *Journ. Geophys. Res.*, 109, B07305, doi:10.1029/2003JB002606.

These publications may be obtained online from;

<http://www.seismo.berkeley.edu/~dreger/ChiandDreger2002GRL.pdf>  
[http://www.seismo.berkeley.edu/~dreger/ChiDreger2004JGR\\_ChiChi.pdf](http://www.seismo.berkeley.edu/~dreger/ChiDreger2004JGR_ChiChi.pdf)

#### **4. Describe any instances where you are aware that your results have been used in industry**

The finite-source parametric information that we have obtained for the large aftershocks as well as the moment magnitudes for the moderate aftershocks is being used by researchers participating in the Next Generation Attenuation (NGA) project.

#### **5. Methodology employed**

To determine seismic moment tensors the method of complete, low frequency waveform inversion was used. This method is described in Pasyanos et al. (1996). Event locations were evaluated using a grid search method (Dreger et al., 1998; Uhrhammer et al., 2001). Finite-source parameters were determined using the method described in (Dreger and Kaverina, 2000; Kaverina et al., 2002; and Chi et al., 2001). This method was developed under the Lifelines project 701.

- Chi, W-C, D. Dreger and A. Kaverina (2001). Finite-source modeling of the 1999 Taiwan (Chi-Chi) earthquake derived from a dense strong motion network, *Bull. Seism. Soc. Am.*, 91, 1144-1157.
- Dreger, D., R. Uhrhammer, M. Pasyanos, J. Franck, and B. Romanowicz (1998). Regional and Far-Regional Earthquake Locations and Source Parameters using Sparse Broadband Networks: A Test on the Ridgecrest Sequence, *Bull. Seism. Soc. Am.*, 88, 1353-1362.
- Dreger, D. S. and A. Kaverina (2000). Seismic remote sensing for the earthquake source process and near-source strong shaking: a case study of the October 16, 1999 Hector Mine earthquake, *Geophys. Res. Lett.*, 27, 1941-1944.
- Kaverina, A., D. Dreger and E. Price (2002). The combined inversion of seismic and geodetic data for the source process of the 16 October 1999 Mw7.1 Hector Mine, California, earthquake, *Bull. Seism. Soc. Am.*, 92, 1266-1280.
- Pasyanos, M. E., D. S. Dreger, and B. Romanowicz (1996). Toward real-time estimation of regional moment tensors, *Bull. Seism. Soc. Am.*, 86, 1255-1269.
- Uhrhammer, R. A., D. Dreger and B. Romanowicz (2001). Best practice in earthquake location using broadband three-component seismic waveform data, *Pure. Appl. Geophys.*, 158, 259-276.

#### **6. Other related work conducted within and/or outside PEER**

N/A

#### **7. Recommendations for the future work: what do you think should be done next?**

There are a number of other M6 aftershocks not contained on the project event list that now have available seismic waveform data. Future studies of these events can provide additional constraints on the fault structure activated by the mainshock and also on the nature of strong ground motion attenuation in Taiwan.

#### **8. Author(s), Title, and Date for the final report for this project**

Dreger, Chi, and Rhie, Seismic Moment Tensors and Finite-Source Analysis of Chi-Chi Aftershocks, January 2004.