FINAL TECHNICAL REPORT
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BROADBAND MODELING LOCAL AND REGIONAL SEISMOGRAMS; SOUTHERN CALIFORNIA

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ABSTRACTS

1. Slip history and dynamic implications of the 1999 Chi-Chi, Taiwan, earthquake

Chen Ji, Donald V. Helmberger, David J. Wald, and Kuo-Fong Ma
(*Journal of Geophysical Research,* Vol. 108, No. B9, 2412, doi:10.1029/ 2002JB001764, 2003)
Short title: Slip History of the 1999 Chi-Chi Earthquake

Abstract. We investigate the rupture process of the 1999 Chi-Chi, Taiwan, earthquake using extensive near-source observations, including three-component velocity waveforms at 36 strong motion stations and 119 GPS measurements. A three-plane fault geometry derived from our previous inversion using only static data [*Ji et al.*, 2001] is applied. The slip amplitude, rake angle, rupture initiation time, and risetime function are inverted simultaneously with a recently developed finite fault inverse method that combines a wavelet transform approach with a simulated annealing algorithm [*Ji et al*., 2002b]. The inversion results are validated by the forward prediction of an independent data set, the teleseismic P and SH ground velocities, with notable agreement. The results show that the total seismic moment release of this earthquake is 2.7 x 10^{20} N m and that most of the slip occurred in a triangular-shaped asperity involving two fault segments, which is consistent with our previous static inversion. The rupture front propagates with an average rupture velocity of ~2.0 km s^{-1}, and the average slip duration (risetime) is 7.2s. Several interesting observations related to the temporal evolution of the Chi-Chi earthquake are also investigated, including (1) the strong effect of the sinuous fault plane of the Chelungpu fault on spatial and temporal variations in slip history, (2) the intersection of fault 1 and fault 2 not being a strong impediment to the rupture propagation, and (3) the observation that the peak slip velocity near the surface is, in general, higher than on the deeper portion of the fault plane, as predicted by dynamic modeling.

2. Complex Rayleigh waves resulting from deep sedimentary basins

Brian Savage and Don V. Helmberger
(*Earth and Planetary Science Letters* 218, 2004, 229-239)
Short title: Complex Rayleigh waves

Abstract. Two earthquakes in northern Mexico recorded by TriNet stations in southern California show complex surface wave propagation through the Salton Trough. Stations contained in a narrow corridor extending from the Salton Trough north towards the Central Valley, California show recorded waveforms with two Rayleigh wave arrivals. The time separation between the Rayleigh wave arrivals is nearly constant beyond the northern edge of the Salton Trough. We are able to reproduce both arrivals with a simple 1D model of a low velocity, deep basin in the Salton Trough. The slower Rayleigh wave is propagating within the sediments of the basin, while the faster Rayleigh wave propagates mainly in faster, basement rock. Further, we reproduce the constant time

separation through the implementation of a simple 2D model. This 2D model has a low velocity, deep basin near the source and a crust without a basin at distances greater than 200 km.

3. Site Response from Incident *Pnl* Waves

Brian Savage and Don V. Helmberger
(*Bulletin of the Seismological Society of America*, Vol. 94, No. 1, pp. 357-362, February 2004)

Abstract. We developed a new method of determining site response and amplification for use in hazard analysis and station corrections. The method employs the conversion of *P* to *S* energy beneath a soft-rock station, which results in complex receiver functions that are frequency and amplitude dependent. At low frequencies (<0.1 Hz), the ratio of vertical to radial energies for *Pnl* appear uniform across the TriNet array, where shallow structures can be neglected. Ratios of high-frequency energies (>0.5 Hz) can be normalized to these low-frequency levels to quantify the amount of high-frequency amplification. Our results agree with previous studies of the Los Angeles Basin and provide the means of calibrating station responses at high frequencies.

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Non-Technical Summary

In recent years, geologists and geophysicists have witnessed a revolution in the development and implementation of an array of new tools for measuring motions of the earth's crust, including global positioning satellites, interferometric synthetic aperture radar, and broadband digital seismic systems, allowing tremendous advances in motion detection accuracy. As demonstrated in this report, we can successfully model the near-in data with far-fewer parameters than reported to date using our recently developed analytical tools (wavelet transforms, modified annealing, etc.). We demonstrate the reverse process of predicting local shaking from teleseismic data as well. Thus we can make rapid assessments of earthquake damage following major global events which proves very useful in providing emergency services.

Investigations

There have not been many studies on the source characteristics of Great Earthquakes. One such study involved the comparison of the Loma Prieta event with the 1906 San Francisco Earthquake, Wald *et al*. (1993). The project involved modeling the teleseismic waveforms from the 1908 Carnegie Report (Collection of 1906 records) and compared with some modern events recorded on the same instruments, Göttingen Germany, etc. After calibrating paths, we simulated the 1906 event as a distributed fault. The model was used to construct a strong motion field using asperities taken from the detailed studies of Loma Prieta (Wald *et al*., 1991). Peak velocity values of up to 230 cm/sec at periods of about 6 secs were produced in the near-field with reasonable estimates of rise-time (5 secs actual time it takes for the offset to occur). Reducing the rise-time by 40% increases peak velocities by about 20% and greatly increases the accelerations depending on period. These velocity simulations were considered <u>too high</u> by most strong motion

engineers. However, recent near-in observations (Chi-Chi) are even higher. The Chi-Chi event is unique in its wealth of data and strength. It also has an abundance of hanging vs. footwall motions that can be studied with respect to possible thrust events in and around Los Angeles or beneath Cascadia (*see Abstract 1*). Our efforts in the development of advanced "Cut and Paste" methods will provide calibrated paths and the means to more accurately determine depths and directivity. Refined depths will greatly help Hauksson's efforts in generating SCEC velocity models since this is, probably, his biggest source of error. Our efforts will also contribute to several NEHRP research priorities involving real-time source estimation and Shake-Map tool development (Element I), in particular, the use of TriNet waveform data to invert for source parameters, and methods for using analytical and numerical data together in shake-map construction (*see Abstracts 2 and 3*)

Results

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<u>Bibliography</u>

Ji, Chen, D. V. Helmberger, T.-R. Song, K.-F. Ma, and D. J. Wald, Slip distribution and tectonic implication of the 1999 Chi-Chi, Taiwan, Earthquake, *Geophys. Res. Lett.*, *28*, No. 23, 4379-4382, 2001.

Ji, Chen, D. V. Helmberger, D. J. Wald, and K.-F. Ma, Slip history and dynamic implications of the 1999 Chi-Chi, Taiwan earthquake, *J. Geophys. Res.*, *108*, No. B9, 2412, 2003.

Ji, Chen, D. Wald, and D. V. Helmberger, Source Description of the 1999 Hector Mine, California Earthquake; Part I: Wavelet Domain Inversion Theory and Resolution Analysis, *Bull. Seismol. Soc. Am., 92*, No. 4, 1192-1207, 2002.

Ji, Chen, D. Wald, and D. V. Helmberger, Source Description of the 1999 Hector Mine, California Earthquake; Part II: Complexity of Slip History, *Bull. Seismol. Soc. Am., 92*, No. 4, 1208-1226, 2002.

Helmberger, D. V., Theory and application of synthetic seismograms, in *Earthquakes: Observation, Theory and Interpretation,* LXXXV, corso, 174-222, Soc. Italiana di Fisica, Bologna, Italy, 1983.

Ma, K.-F., T.-R. A. Song, S.-J. Lee, and H.-I. Wu, Spatial slip distribution of the September 20, 1999, Chi-Chi, Taiwan, earthquake (Mw 7.6): Inverted from teleseismic data, *Geophys. Res. Lett., 27*, 3417-3420, 2000.

Savage, B. and D. V. Helmberger, Complex Rayleigh waves resulting from deep sedimentary basins, *Earth Planet. Sci. Lett., 218*, 229-239, 2004.

Savage, B. and D. V. Helmberger, Site response from incident *Pnl* waves, *Bull. Seismol. Soc. Am., 94*, No. 1, 357-362, 2004.

Wald, D. J. and T. H. Heaton, Spatial and temporal distribution of slip for the 1992 Landers, California, earthquake, *Bull. Seismol. Soc. Am., 84*, 668-691, 1994.