# CHARACTERIZING EARTHQUAKE SLIP MODELS FOR THE PREDICTION OF STRONG GROUND MOTION

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## SUMMARY

Over the past fifteen years, slip models have been derived for enough crustal earthquakes that we can now identify systematic features of these slip models and their scaling with seismic moment for use in the prediction of strong ground motion. We have used two approaches in our analysis of these slip models. The first approach is to use a set of parameters to quantify in a deterministic manner the properties of slip models and asperities. The second approach is to quantify the heterogeneity of slip on the fault surface by its two-dimensional Fourier transform (the wavenumber spectrum). In developing a method of generating slip models of future earthquakes, we can use the asperity characteristics derived from the first approach to constrain a model of the wavenumber spectrum based on the second approach.

## INTRODUCTION

A large amount of work has been done in recent years to estimate the distribution of slip on the fault surface during earthquakes. Generally, these slip models are derived from longer period ground motions: strong-motion velocity and displacement, and teleseismic velocity seismograms. At these longer periods, ground motions are predominantly deterministic and their waveforms can in general be accurately modeled using simple descriptions of the source and crustal structure. The opposite situation exists for the prediction of high-frequency strong ground motions. Ground motions at high frequencies are predominantly stochastic, and their waveforms in general cannot be accurately modeled using simple descriptions of the source and crustal structure. However, preliminary evidence (e.g. Hartzell et al., 1996; Kamae and Irikura, 1998; Somerville, 1993; Somerville et al., 1996, Wald et al., 1988) suggests that variable slip models derived from longer-period ground-motion recordings are relevant for the prediction of higher-frequency ground motions. For both short and long periods, one of the main uncertainties in the prediction of strong ground motion is the uncertainty in appropriate methods of characterizing the source characteristics of future earthquakes. This paper describes information for characterizing the slip models of future earthquakes for use in the prediction of strong ground motion.

An important aspect of the problem of characterizing the earthquake source is the degree of fault heterogeneity or roughness. The heterogeneity may be manifested as local variations in static slip, slip velocity, or rupture velocity. It is possible that all three are interdependent and that each contributes significantly to the high-frequency radiation. There is little agreement, however, in exactly how these characteristics are physically related. In most broadband strong- motion simulation procedures (e.g. Somerville et al., 1996), the spatial variations in slip are modeled in a deterministic manner because they are fairly well constrained by data.

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Variations in rupture velocity and slip velocity are usually modeled in a stochastic manner, because at present it is difficult to constrain these variations in a deterministic manner. However, we can include deterministic variations in rupture velocity and slip velocity when enough information becomes available to constrain them. Accordingly, this paper focuses on characterizing the spatial variation of slip on the fault. The slip models of shallow crustal earthquakes are characterized by strong spatial variation in slip on the fault surface, including asperities (which we define as regions of large slip on the fault).

This paper analyzes the characteristics of slip models of fifteen crustal earthquakes. Except for the 1978 Tabas and 1995 Kobe earthquakes, all of the earthquakes occurred in western North America. The slip models were derived in a fairly uniform manner from the inversion of lowpass-filtered near-source strong motion recordings and teleseismic body waves. We quantify the characteristics of asperities of individual earthquakes and examine their average characteristics. We then examine how the slip models scale with seismic moment. We use the spatial wavenumber spectrum as an additional method of describing the heterogeneity of slip on the fault surface.

## SLIP MODELS

The slip models of past earthquakes show that the spatial variation of slip (and seismic wave radiation) over the fault surface is an important aspect of the earthquake source. Summaries of slip models of these earthquakes are given by Mendoza and Hartzell (1988b) and Heaton (1990). Enough slip models have been derived over the past twenty years that we can now examine their systematic features. We can then use these systematic features to generate slip models for the prediction of strong ground motion.

The earthquakes analyzed in this study are listed in Table 1. All fifteen of these crustal earthquakes have rupture models in which the slip varies spatially over the fault surface. In this study, we use a rectangular representation of the fault rupture because our objective is to develop methods of generating slip models on rectangular fault planes. In most slip model inversions, the rectangular dimensions of the fault are chosen to be at least large enough to accommodate the entire fault rupture, and so they generally overestimate the actual dimensions of the rupture area. Accordingly, we reduced the dimensions of the rectangular fault slip models using a standard criterion for trimming the edges of the slip models (Somerville et al., 1999). The slip duration (or dislocation rise time), listed Table 1, is based on the time window length for the five events having a single time window and on an assessment of the predominant rise time for the ten events having multiple time windows in the slip model inversion.

## ANALYSIS OF FAULT ASPERITIES

An asperity is a region on the fault rupture surface that has large slip relative to the average slip on the fault. For the purposes of this study, we have defined an asperity as a rectangular region in which the slip exceeds, in a specified way, the slip averaged over the entire fault rupture. We chose a rectangular definition of asperities to facilitate the generation of slip models of future earthquakes using this simple geometry. An asperity is initially defined to enclose fault elements whose slip is 1.5 or more times larger than the average slip over the fault and is subdivided if any row or column has an average slip less than 1.5 times the average slip. The asperity is then trimmed until all of the edges have an average slip equal to or larger than 1.25 times the slip averaged over the entire rupture area. A criterion was used to limit the size of the smallest asperity (Somerville et al., 1999). As an example, the analysis of asperities of the 1989 Loma Prieta earthquake is shown at the top of Figure 1.

The number of asperities in the slip models of the fifteen events ranges from 1 to 6, and shows no clear dependence on seismic moment. In all, the fifteen earthquakes have 39 asperities, or 2.6 asperities each on average. We analyzed the distribution of slip contrast (the average slip on the asperities as a fraction of the average slip of the overall rupture) and normalized asperity area (the area of the asperity as a fraction of the fault rupture area) in this set of 39 asperities. The slip contrast has an asymmetrical distribution, with most asperities having a ratio between 1.5 and 3.0. Individual asperities typically occupy a few percent of the rupture area, with the largest asperity on average occupying 17.5% of the overall rupture area.

Asperities on both strike-slip and dip-slip faults tend to have along-strike length to down- dip width ratios (aspect ratios) of about 1, except for the two Nahanni events which each have a long, narrow asperity at the top of the fault rupture. In contrast, the mainshock rupture zones of the seven strike-slip faults (including the oblique Loma Prieta earthquake) have an average aspect ratio of 2.75, whereas the those of the eight dip-slip faults (including the oblique North Palm Springs event) have an average aspect ratio of 1.6. The centers of asperities of both strike-slip and dip-slip faults are distributed fairly evenly both along strike and down-dip.

## SCALING OF PARAMETERS OF SLIP MODELS WITH SEISMIC MOMENT

We can use the large range of seismic moment values of the fifteen earthquakes listed in Table 1 to look for systematic features of the scaling of slip models with magnitude. These scaling relations, listed in Table 2, are important for establishing general rules for developing source models for simulating strong ground motions. The simplest scaling relationship is a self-similar one in which the basic properties of the slip models, and of the asperities that they contain, remain scale invariant. The basic property of a self-similar system is that events of different sizes cannot be distinguished except by a scale factor.

The relationship between seismic moment and fault parameters is given by:

$$M_o = \mu D\ L\ W$$

where $M_o$ is seismic moment, $\mu$ is shear modulus, D is average fault displacement, L is fault length and W is fault width. In a self-similar system, increase in seismic moment occurs by proportionately equal changes in average slip D, fault length L and fault width W so that the stress drop (proportional to the ratio of D to L or W) remains constant. Also, the duration of slip on the fault $T_R$ increases in proportion to D, or equivalently to L or W, so that the slip velocity (the ratio of D to $T_R$) remains constant. In this self-similar model, the size of asperities in relation to L (and W) remains constant, their average slip in relation to D (slip contrast) remains constant, and the number of asperities remains constant.

The self-similar model is convenient to use, and in many instances its use can be justified because it provides a reasonably good description of nature. For example, Tanioka and Ruff (1997) found that the teleseismic source time functions of large earthquakes are compatible with a self-similar scaling model. In this study of crustal earthquakes, we find that the scaling of the fault parameters described above with seismic moment is also reasonably well fit by a self-similar model (Somerville et al., 1999). We expect that limits in the dimensions of faults (especially the downdip width W) are reached for very large crustal earthquakes, especially strike-slip earthquakes, causing departures from this self-similar model (Shimazaki, 1986). However, for the moderate-sized crustal earthquakes that make up most of the data set that we analyze here, we conclude that the self-similar model is a reasonable approximation.

The scaling relations are summarized in Table 2. Except where noted, all of the relationships use cgs units.
The fault rupture areas used in these relations reflect the zone of the fault that radiated seismic energy, and so this relation is directly relevant to the prediction of strong ground motion. Wells and Coppersmith (1994) derived a relationship between seismic moment and rupture area from a much larger set of crustal earthquakes, primarily using the dimensions of the early aftershock zone. This is a less direct kind of evidence than that derived from the seismic radiation during the mainshock. Nevertheless, the Wells and Coppersmith (1994) relationship for a dataset that includes all styles of faulting is very similar to the one derived here.

We analyzed the distribution of slip contrast averaged over the asperities of each earthquake. The slip contrast is concentrated in the range of 1.5 to 2.8, with an average value of about 2, and shows no clear dependence on seismic moment, consistent with a self-similar scaling relation. Events having the largest slip contrasts are the Morgan Hill event, the two Nahanni events, and the Tabas event.

We also analyzed the combined area of asperities as a fraction of the fault rupture area of each earthquake. The ratio of the combined area of asperities to the total rupture area on average is 22%, and shows no clear dependence on seismic moment, consistent with self-similar scaling. The two events in which asperities cover a large part of the fault are the Borah Peak and Coyote Lake events. The four events in which asperities cover a small part of the fault are the Loma Prieta, North Palm Springs, Morgan Hill and Whittier Narrows earthquakes. The area of the largest asperity in each slip model scales in an approximately self-similar way, and on average occupies 17.5% of the total rupture area. In summary, asperities make up about 22% of the total rupture area on average, and have a slip contrast of 2 on average, independent of seismic moment, and thus account for 44% (that is, 2 times 22%) of the total slip on the fault.

## WAVENUMBER SPECTRUM ANALYSIS OF SPATIAL HETEROGENEITY IN SLIP

In the above analysis, we have made some approximate quantitative estimates of the parameters of slip models and analyzed their scaling with seismic moment. In this section, we follow an alternative approach to quantifying slip models for use in developing characteristic slip models of future earthquakes. To characterize the spatial variation in slip in a way that is useful for constructing slip models, we have analyzed the 2-D Fourier transforms of the slip functions summarized above. In taking the Fourier transform, we are viewing the slip function as the sum of a series of slip functions each of which is a 2-D sinusoidal function having a single spatial wavelength. The two dimensions are the dimension along strike and the dimension downdip. The Fourier transform describes the relative amplitudes of these different spatial wavelengths in the slip model.

It is conventional to describe the spatial wavelength in terms of its reciprocal, the spatial wavenumber. Small wavenumbers are equivalent to long wavelengths and represent broad fluctuations of slip over the fault surface, while large wavenumbers are equivalent to short wavelengths and represent local fluctuations over the fault surface. The wavenumber spectra of the 1989 Loma Prieta earthquake in the along strike and down-dip directions are shown at the bottom of Figure 1. Generally, the strike-slip and oblique-slip earthquakes have a more rapid decay of wavenumber in the along-strike direction than in the down-dip direction, indicating more rapid variation in slip down-dip than along-strike, relative to the dimensions of the fault. In contrast, the wavenumber spectra of dip-slip faults have more similar decay of wavenumber along-strike and down-dip.

We obtained the parameters of a wavenumber spectral model of the slip distribution in earthquakes by fitting a simple functional form to the wavenumber spectra of individual earthquakes We used 2-D Butterworth filters to model the wavenumber amplitude spectrum. The corner wavenumbers $KC_x$ and $KC_y$ in the along-strike and down-dip directions respectively were assumed to each have a self-similar scaling with moment magnitude M. For self-similar scaling, the corner wavenumber is inversely proportional to the one-third power of seismic moment, and the logarithm of the corner wavenumber is proportional to one-half the moment magnitude. The least squares fit resulted in the following model:

$\log KC_x = 1.72 - 0.5\,M$; $\log KC_y = 1.93 - 0.5\,M$

The Butterworth filters have 2.0 poles, and the corner wavenumbers are approximately log normally distributed with a standard error of 0.26. The wavenumber amplitude is given by:

$$amp(kx,ky) = \frac{1}{\sqrt{1+\left(\left(\frac{kx}{KC_x}\right)^2+\left(\frac{ky}{KC_y}\right)^2\right)^{2.0}}}$$

In the bottom of Figure 1, we compare the fit of this model to the 1989 Loma Prieta earthquake. The spectrum falls off as the inverse of the wavenumber squared at high wavenumbers, consistent with the model of Herrero and Bernard (1994). Herrero and Bernard (1994) based their model on the assumption of self-similarity in slip distribution, independent of seismic moment. They showed that this is consistent with the stochastic fault model of Andrews (1981), which has a stress drop that decays as the inverse of the wavenumber. The model of Herrero and Bernard (1994) is also consistent with the fractal model of Frankel (1991) when the fractal dimension is 2. This suggests that our wavenumber model may be reliable for higher wavenumbers, and that given our current state of knowledge, it is reasonable to use our empirical wavenumber model to generate slip models for the prediction of high-frequency ground motion.

Herrero and Bernard (1994) show that the wavenumber-squared model, when combined with the assumptions of constant rupture velocity and scale-dependent rise time, results in a kinematic source model whose frequency spectrum falls off as the inverse of the frequency squared. This frequency squared decay was first proposed by Aki (1967) and is commonly found to describe the source spectra of earthquakes (e.g. Houston and Kanamori, 1986).

## CONCLUSIONS

We have used two approaches in our analysis of the slip models of crustal earthquakes. The first approach is to use a set of parameters to quantify in a deterministic manner the properties of slip models and asperities. We defined an asperity as a region in which the slip is larger by a prescribed amount than the average slip over the fault surface. We found that slip models and the asperities on them scale in a self-similar manner with increasing seismic moment. In this self-similar system, increase in seismic moment occurs by proportionately equal changes in average slip D, fault length L and fault width W so that the stress drop (proportional to the ratio of D to L or W) remains constant. Also, the duration of slip on the fault $T_R$ increases in proportion to D, or equivalently to L or W, so that the slip velocity (the ratio of D to $T_R$) remains constant. The size of asperities in relation to L (and W) remains constant, their average slip in relation to D (slip ratio) remains constant, and the number of asperities remains constant.

Some quantitative measures of these self-similar scaling relationships are as follows. The combined area of asperities scales in a self-similar way with increasing seismic moment, being proportional to the two-thirds power of seismic moment. The combined area of asperities on average occupies 22% of the total rupture area. The area of the largest asperity in each slip model also scales in an approximately self-similar way, and on average occupies 17.5% of the total rupture area. The slip contrast of asperities (the ratio of average slip on asperities to average slip over the whole rupture surface) is independent of seismic moment, consistent with the self-similar scaling law, and its average value for the events studied is about 2. On average, the slip duration scales in a self-similar way with seismic moment, being proportional to the one-third power of seismic moment. The rupture velocities of the slip models fall within the fairly narrow range of 2.4 to 3.0 km/sec and show no dependence on seismic moment.

An alternative method of representing the average characteristics of the slip models of past earthquakes is to compute the 2-D Fourier transforms of the slip functions of these earthquakes and analyze the resulting spatial wavenumber spectra. We derived a model for the wavenumber spectrum which falls off as the inverse of the wavenumber squared at high wavenumbers, consistent with the model of Herrero and Bernard (1994). This wavenumber spectral model is also consistent with the stochastic fault model of Andrews (1981) and the fractal model of Frankel (1991) when the fractal dimension is 2. Herrero and Bernard (1994) show that the wavenumber squared model, when combined with the assumptions of constant rupture velocity and scale-dependent rise time, results in a kinematic source model whose frequency spectrum falls off as the inverse of the frequency squared, which is the standard model of the earthquake source spectrum (Aki, 1967).

The scaling relations of earthquake rupture models that we have developed are based on a relatively small set of events, so it is possible that they will change as new and potentially surprising information is obtained from future earthquakes. Denser networks of near-fault recording stations and improved methods of accounting for the effects of lateral variations in geological structure will be required to obtain more highly resolved images of earthquake rupture processes. This paper deals mainly with the characteristics of earthquake rupture models inferred from lowpass filtered strong motion recordings. Techniques for more adequately characterizing the seismic radiation from faults at high frequencies, such as that developed by Kaheki et al. (1996), need to be developed to provide a more reliable basis for predicting broadband ground motions for engineering design and analysis.

## REFERENCES

Aki, K. (1967). Scaling law of seismic spectrum, *J. Geophys. Res.*, **72**, 1217-1231.
Andrews, D.J. (1981). A stochastic fault model, 2. Time-independent case. *J. Geophys. Res.*, **86**, 10821-10834.
Frankel, A. (1991). High-frequency spectral falloff of earthquakes, fractal dimension of complex rupture, *b* value, and the scaling strength on fault. *J. Geophys. Res.*, **96**, 6291-6302.
Hanks, T.C. and H. Kanamori (1979). A moment-magnitude scale, *J. Geophys. Res.*, **84**, 2348-2350.
Hartzell, S. H. (1989). Comparison of seismic waveform inversion techniques for the rupture history of a finite fault: application to the 1986 North Palm Springs, California, earthquake, *J. Geophys. Res.*, **94**, 7515-7534.
Hartzell, S. H. and T. H. Heaton (1983). Inversion of strong ground motion and teleseismic waveform data for the fault rupture history of the 1979 Imperial Valley, California, earthquake, *Bull. Seism. Soc. Am.*, **73**, 1553-1583.
Hartzell, S. H. and T. H. Heaton (1986). Rupture history of the 1984 Morgan Hill, California, earthquake from the inversion of strong motion records, *Bull. Seism. Soc. Am.*, **76,** 649-674.
Hartzell, S. H. and M. Iida (1990). Source complexity of the 1987 Whittier Narrows, California, earthquake from the inversion of strong motion records, *J. Geophys. Res.*, **95**, 12475-12485.
Hartzell, S. H. and C. Mendoza (1991). Application of an iterative least-squares waveform inversion of strong-motion and teleseismic records to the 1978 Tabas, Iran, earthquake, *Bull. Seism. Soc. Am.*, **81**, 305-331.

Hartzell, S.H., C. Langer, and C. Mendoza (1994). Rupture histories of Eastern North American earthquakes, *Bull. Seism. Soc. Am.* 84, 1703-1724.

Hartzell, S.H., P. Liu and C. Mendoza (1996). The 1994 Northridge, California earthquake: Investigation of rupture velocity, rise time, and high-frequency radiation. *J. Geophys. Res.*, **101**, 20,091-20,108.

Heaton, T. H. (1982). The 1971 San Fernando earthquake; a double event? *Bull. Seism. Soc. Am.*, **72**, 2037-2062.

Heaton, T. H. (1990). Evidence for and implications of self-healing pulses of slip in earthquake rupture, *Phys. Earth Planet. Interiors,* **64**, 1-20.

Herrero, A. and P. Bernard (1994). A kinematic self-similar rupture process for earthquakes. *Bull. Seism. Soc. Am.,* **84**, *1216-1228.*

Houston, H. and H. Kanamori (1986). Source spectra of great earthquakes: teleseismic constraints on rupture process and strong motion. *Bull. Seism. Soc. Am.,* **76**, 19-42.

Kamae, K. and K. Irikura (1998). Source model of the 1995 Hyogo-ken Nanbu earthquake and simulation of near-source ground motion, *Bull. Seism. Soc*. Am. **88**, 400-412.

Kaheki, Y., K. Irikura, and M. Hoshiba (1996). Estimation of high-frequency wave radiation areas on the fault plane of the 1995 Hyogo-ken Nanbu earthquake by the envelope inversion of seismograms, *J. Phys. Earth* **44**, 505-517.

Liu, H. L. and D. V. Helmberger (1983). The near-source ground motion of the 6 August 1979 Coyote Lake, California, earthquake, *Bull. Seism. Soc. Am.*, **73**, 201-218.

Mendoza, C. and S. H. Hartzell (1988a). Inversion for slip distribution using GDSN P waves: North Palm Springs, Borah peak, and Michoacan earthquakes, *Bull. Seism. Soc. Am.,* **78,** 1092-1111.

Mendoza, C. and S. Hartzell (1988b). Aftershock patterns and mainshock faulting, *Bull. Seism. Soc. Am.,* **78**, 1438-1449.

Somerville, P.G. (1993). Engineering applications of strong ground motion simulation, *Tectonophysics*, **218**, 195-219.

Somerville, P.G., D.J. Wald, and N.F. Smith (1993). Prediction of the near-source ground accelerations of the Loma Prieta earthquake using a heterogeneous slip model. Unpublished manuscript.

Somerville, P., C.K. Saikia, D. Wald, and R. Graves (1996). Implications of the Northridge earthquake for strong ground motions from thrust faults, *Bull. Seism. Soc. Am.,* **86,** S115- S125.

Somerville, P.G., K. Irikura, R. Graves, S. Sawada, D. Wald, N. Abrahamson, Y. Iwasaki, T. Kagawa, N. Smith and A. Kowada (1999). Characterizing earthquake slip models for the prediction of strong ground motion. *Seismological Research Letters*,70, 59-80.

Tanioka, Y. and L.J. Ruff (1997). Source time functions. *Seismological Research Letters* **68**, 386-397.

Wald, D.J., L.J. Burdick and P.G. Somerville (1988). Simulation of acceleration time histories close to large earthquakes. *Earthquake Engineering and Soil Dynamics II - Recent Advances in Ground Motion Evaluation*, Geotechnical Special Publication 20, J. Lawrence Von Thun, ed., 430-444.

Wald, D. J., D. V. Helmberger and S. H. Hartzell (1990). Rupture process of the 1987 Superstition Hills earthquake from the inversion of strong-motion data, *Bull. Seism. Soc. Am.,* **80**, 1079-1098.

Wald, D. J., D. V. Helmberger and T. H. Heaton (1991). Rupture model of the 1989 Loma Prieta earthquake from the inversion of strong motion and broadband teleseismic data, *Bull. Seism. Soc. Am.* **81**, 1540-1572.

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

Wald, D.J., T.H. Heaton, and K.W. Hudnut (1996). The slip history of the 1994 Northridge, California earthquake determined from strong motion, teleseismic, GPS and leveling data. *Bull. Seism. Soc. Am.* **86**, S49-S70.

Wald, D.J. (1996). Slip history of the 1995 Kobe, Japan, Earthquake determined from Strong Motion, Teleseismic, and Geodetic data, *J. Physics of the Earth*, **44**, 489-503.

Wells, D. L. and K. J. Coppersmith (1994). Analysis of empirical relationships among magnitude, rupture length, rupture area, and surface displacement. *Bull. Seism. Soc. Am.* **84**, 974-1002.