SEISMIC MONITORING AND MODELING OF EARTHQUAKE PROCESSES FOR PREDICTION

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Abstract

To develop earthquake prediction research as a sound science, it is essential to construct physical models with predictive capabilities and to monitor the observables that constrain the parameters of the models. The present paper proposes an approach toward this goal by using the following recently published results as building blocks: (1) The extrapolation of laboratory results to the field observations on earthquake faults by Ohnaka and his colleagues; (2) The discovery of temporal change in frequency dependent seismic attenuation and in the magnitude-frequency relation related to stress re-distribution after 1995 Hyogoken Nanbu earthquake by Hiramatsu and his co-workers; (3) The discovery of a systematic relationship between moment magnitude and the sub-event size from strong motion records for earthquakes in eastern north America and elsewhere by Beresnev and Atkinson; (4) The estimation of seismic energy from an earthquake taking into account the scattering and absorption loss by Sato and his colleagues, which will enable an accurate estimation of temporal change in apparent stress, and (5) The computer simulation of earthquake fault ruptures by Ward. These simulations can assimilate available data from geological studies on active faults in the modeling of earthquake occurrence. The key concept unifying all of the above studies is the slip weakening model of the rupture over a heterogeneous fault plane. Slip weakening friction might be too simple, but we believe that it is a good starting point for our purpose.

Introduction

At the first ACES workshop in Australia, 1999, an important question was raised by Matsu`ura whether large earthquakes can be separated from small ones. Aki (2000[11]) gave a definitely positive answer based upon various observations of earthquake processes and seismogenic structures. For Southern California, the boundary separating large and small earthquake behaviors is at M～5. The conclusion that the small earthquakes have different behaviors than large ones opens a possibility for deterministic modeling of earthquake occurrence for prediction. It was recognized, however, that earthquake systems involves non-linear physics with many degrees of freedom. In the present paper, we try to find the starting point for a sound scientific approach for earthquake prediction research by uniting several recent studies relevant to this goal.

The basis of the unification is a model of the earthquake fault plane composed of sub-events separated by <*barriers*>, in which sub-events are characterized by a slip weakening friction law. Testing the validity of this model and estimating its parameters have been made by using a variety of observations including: (1) the power spectra of strong motion accelerograms (Papageorgiou and Aki, 1983[37], 1985{38}, Chin and Aki, 1991[14]), and the systematic dependence of model parameters on magnitude for major California earthquakes (Aki, 1992[8], 1995[9], 1996[10], 2000[11]), (2) the departure of the spectral scaling law from the self-similarity (Chouet et al., 1978[15], Iio, 1986[21], 1991[22], Jin et al. 2000[25]), (3) the departure of the frequency-magnitude relation from self-similarity (Aki, 1987[7]), (4) the temporal correlation between coda Q^{-1} and seismicity in California (Jin and Aki 1989[23] 1993[24]), (5) the frequency dependence of seismic attenuation observed in seismic active regions (Aki, 1980[3], Adams and Abercrombie,1998[1], Yoshimoto et al.,1998[52]), (6) the unique width of earthquake fault zones from the characteristics of the seismic trapped modes (Li et al., 1994[29], 1997[30], 1998[31], 1999[32]), and (7) the existence of the upper fractal limit for the fault trace geometry (Okubo and Aki, 1987[36]).

The idea behind the *barrier* model originated from numerical simulations of faulting by Das and Aki (1977[16] [17]). And the so called <*Heaton pulse*>, first found by Housner and Trifunac (1967[20]) in the near source strong motion seismogram of the 1966 Parkfield earthquake has been one of the observational bases for the *barrier* model as described by Aki (1979[2]). How the observations listed above contributed to the development of the model is described in Aki (1979[2], 1980[4], 1996[10], 2000[11]). Some of the concepts underlying the model, for example, the existence of a minimum earthquake size for a given seismic region, were supported by independent observations (e.g., Sacks and Rydelek, 1995[42], Rydelek and Sacks, 1996[41]). In the present paper, we present recently published investigations that further support the model, and we propose a path to proceed toward the goal of earthquake prediction.

The importance of the size of brittle zone in the earthquake physics has been recognized at both transform and subduction zone plate boundaries (Scholz, 1994[44], 1997[45], Romanovicz, 1992[40], Shimazaki,1986[46], Kanamori and Allen, 1986[26], Mogi, 1969[33]). For modeling the earthquake process, however, we need to know the scale of the nucleation zone as well as that of sub-event size. Tom Jordan (personal communication) coined the word < *inner scale*> to these somewhat ambiguous parameters of earthquake process. We like the word <*inner*> because it implies some fundamental control of the process. In the present paper, we bring out recent discoveries about the inner scale of the earthquake process.

The first inner scale: the size of the nucleation zone

Based on a series of systematic, high-resolution laboratory experiments Ohnaka and Shen(1999[34]) concluded that the nucleation zone size and its duration scales with a characteristic length that represents the heterogeneities on the fault surfaces. Ohnaka(2000[35]) extrapolated their laboratory results to the field observation and proposed a specific model of the earthquake nucleation proceeded on a non-uniform fault zone. His model uses the nucleation zone size as the length to scale the seismic moment for earthquakes in a moment range of 10^{13} to 10^{21} Nm., although, Aki(2000[11]) found by summarizing the field observations that the cohesive sizes are in a rather narrow range of few hundred meters to 1-2 kilometers.

Recently, Hiramatsu et al. (2000[19]) found significant changes in the b-value and the coda Q^{-1} in the Tamba region, northeast of the epicenter area of the 1995 Hyogo-ken Nanbu earthquake. They showed that the observations can be explained by tectonic loading through creep on fractures of a few hundred meters size. This supports the model of Jin and Aki (1989[23], 1993[24]) to explain the strong correlation between the b-value and the coda Q^{-1} observed in California and several other areas. Table 1, reproduced from Jin and Aki (1993[24]), summarizes the observations and indicates the characteristic size of earthquake that corresponds to the presumed size of the creep fracture in each area ranging from 100 to 2000 meters

Table 1. The observed correlation between coda Q^{-1} and b-value

Region (Time period)	Coda Q^{-1} (Author)	b-value (Author)	Sign of correlation	Magnitude range for b estimation	Mc
Stone Canyon, CA (July 1973-June 1974)	Increase (Chouet, 1979)	Decrease (Chouet, 1979)	-	0.9 - 3.3	~4
Tangshan, China (1973-1976)	Increase (Jin and Aki, 1986)	Decrease Li et al, 1978	-	1.8 - 5.0	4~5
Misasa, Japan (1980-1982)	Increase (Tsukuda, 1988)	Increase (Imoto, 1988)	+	0.5 - 1.75	1.75
E. Yamanashi, Japan (1981-1983)	Increase (Sato, 1986)	Decrease (Imoto et al, 1986)	-	1.5 - 2.5	2.5
Wellington, region New Zealand (1978-1985)	Increase (Robinson, 1987)	Decrease (Robinson, 1987)	-	2.5 - 5.0	~5
Southern CA (1933-1987)	(Jin & Aki, 1989)	(Jin & Aki, 1989)	+	3.0 -6.0	3.0~3.5
Central CA (1940-1990)	(Jin & Aki, 1993)	(Jin & Aki, 1993)	No	3.0 - 6.0	4.0~4.5

*M_c indicates the characteristic earthquake magnitude; "+" means the correlation is positive and "-" is negative.

The fact that the characteristic size for California agrees with the size of the cohesive zone of the slip weakening model for major earthquakes found from various observations by Aki (1984[6], 1992[8], 1995[9], 2000[11]) suggests that the size of the nucleation zone of a major earthquake might be estimated using data accumulated in existing seismic monitoring networks.

Relevant monitoring observables include: (1) the departure of the magnitude–frequency relation from self-similarity, (2) the frequency dependence of seismic attenuation, (3) the source-controlled upper limit frequency, so called, f_{max} in the strong motion records, (4) the departure of the small earthquakes from self-similarity expressed in the corner frequency independent of magnitude.

As suggested by Aki (2000[11]), the earthquake magnitude that separates large and small earthquakes may be related to the size of cohesive (nucleation) zone.

The second inner scale: the size of the sub-events

A systematic relation has been found between the magnitude and the size of sub-events distributed over the fault plane, called <*barrier interval*>, in terms of the model of Papageorgiou and Aki (1983[37]) for major earthquakes in California as reviewed by Aki (2000[11]). As pointed out by Aki (1992[8], 2000[11]) that the size of <*barrier interval*> decreases systematically with the decreasing magnitude and will intersect the cohesive zone size at magnitude near 5 for major earthquakes in California. This suggests that the minimum magnitude which can occurred on major faults in California is about 5.

Recent investigation by Beresnev and Atkinson (1999[13]) using the model similar to the specific-barrier model showed nearly the same relation for earthquakes in eastern north America and in certain subduction zones. Their resultant sub-fault sizes range between 500 meters to 8 kilometers for moment magnitude of 4.2 to 7.3 events that agrees with Aki (2000[11]) very well.

The observed frequency dependency of seismic attenuation in seismic active region in the lithosphere shows a peak near 1 Hz as first pointed by Aki (1980[3]). Sato and Fehler (1998[43]) were able to simulate such frequency dependent seismic attenuation by specifying scattering characters in a heterogeneous medium. Their results suggest that the observed frequency dependence of seismic attenuation might be related to the dominant size of the heterogeneities in the lithosphere. Adams and Abercrombie (1998[1]), and Yoshimoto et al. (1998[51]) extended the frequency range to 100 Hz on seismic scattering analysis by using borehole data. Their results appear to support Aki`s suggestion about the peak in Q^{-1}.

Computer simulation of earthquake occurrences

In the past decades, there have been a number of attempts to model earthquake processes by computer simulation (e.g. Rice, 1993[39], Knopoff, 1996[27], Ben-Zion, 1996[12], Turcotte, 2000[47], Hashimoto and Matsu'ura, 2000[18]). The present workshop is a manifestation of the increasing interest of the scientific community on the subject and is a timely occasion for exploring directions to proceed for putting the natural phenomena hazardous to the human society within the realm of mathematical physics. Among the several attempts, we like to single out the approach by Ward (1991[48], 1996[49], 1997[50], 2000[51]), because of the effective way in which the parameters of the model were constrained by geological and seismological observations. In particular, he showed (Ward, 1997[50]) how the observed <*inner scales*> mentioned above could be incorporated in the modeling of earthquake processes. We are aware of criticisms on his rather simplistic approach by those who are concerned with the physics of the fault rupture process, but this approach is attractive because of the possibility for an effective assimilation of the geologic and seismological data in modeling the earthquake processes. From this point of view, it is an excellent starting point toward our goal of moving the earthquake prediction into the realm of sound science.

References

[1]Adams, D. A. and R. Abercrombie, 1998, Seismic attenuation above 10 Hz in southern California from coda waves recorded in the Cajon Pass borehole, J. Geophys. Res., 103, 24257-24270.

[2]Aki, K., 1979, Characterization of barriers on an earthquake fault, J. Geophys. Res., 84, 6140-6148.

[3]Aki, K., 1980, Attenuation of shear waves in the lithosphere for frequencies from 0.05 to 25 Hz, Phys. Earth Planet. Int., 21, 50-60.

[4]Aki, K., 1980, Re-evaluation of stress drop and seismic energy using a new model of earthquake faulting, in Source Mechanism and Earthquake Prediction, ed. C. J. Allegre, CNRS, 23-50.

[5]Aki, K., 1982, Scattering and attenuation , Bull. Seismol. Soc. Am., 72, S319-330.

[6]Aki, K., 1984, Asperities, barriers, Characteristic earthquakes, and strong motion prediction, J. Geophys. Res., 89, 5867-5872.

[7]Aki, K., 1987, Frequency-magnitude relation for small earthquakes: a clue to f_{max} of large earthquakes, J. Geophys. Res., 92, 1335-1349.

[8]Aki, K., 1992, High order interrelations between seisnogenic structures and earthquake processes, Tectonophysics, 211, 1-12.

[9]Aki, K., 1995, Interrelation between fault zone structure and earthquake processes, PAGEOPH, 145, 647-676.

[10]Aki, K., 1996, Scale dependence in earthquake phenomena and its relevance to earthquake prediction, Proc. Natl. Acad., Sci., USA, 93, 3740-3747.

[11]Aki. K., 2000, Scale dependence in earthquake processes and seismogenic structures, PAGEOPH, 157, in press.

[12]Ben-Zion, Y., 1996, Stress, slip, and earthquakes in models of complex single-fault system incorporating brittle and creep deformation, J. Geophys. Res., 101, 5677-5706.

[13]Beresnev, I. A. and G. M. Atkinson, 1999, Generic finit-fault model for ground motion prediction in eastern north America, Bull. Seismol. Soc. Am., 89, 608-625.

[14]Chin B. H. and K. Aki, 1991, Simultaneous determination of source, path and site effects on strong ground motion during the Loma Prieta earthquakes-a preliminary result on pervasive non-linear site

effect, Bull. Seismol. Soc. Am., 81, 1859-1884.
[15]Chouet, B., K. Aki and M. Tsujiura,1978, Regional variation of the scaling law of earthquake source spectra, Bull. Seismol. Soc. Am., 68, 49-78.
[16]Das, S. and K. Aki, 1977, A numerical study of two-dimensional spontaneous rupture propagation, Geophys. J. Roy. Astron. Soc., 50, 643-668.
[17]Das, S. and K. Aki, 1977, Fault plane with barriers: a versatile earthquake model, J. Geophys. Res.,82, 5658-5670.
[18]Hashimoto, C. and M. Matsu’ura, 2000, Physical modeling of tectonic loading processes at transcurrent plate boundaries, PAGEOPH, 157, in press.
[19]Hiramatsu, Y., N. Hayashi, M. Furumoto and H. Katao, 2000, Temporal change in coda Q^{-1} and b-value due to the static stress change associated with the 1995 Hyogo-ken Nanbu earthquake, J. Geophys. Res., 105, 6141-6151.
[20]Housner, G. W. and M. D. Trifunac, 1967, Analysis of accelerograms – Parkfield earthquake, Bull. Seismol. Soc. Am., 57, 1193-1220.
[21]Iio, Y., 1986, Scaling relation between earthquake size and duration of faulting for shallow earthquakes in seismic moment between 10^{10} and 10^{25} dyne-cm, J. Phys. Earth, 34, 127-169.
[22]Iio, Y., 1991, Minimum size of earthquakes and minimum value of dynamic rupture velocity, Tectonophysics, 197, 19-25.
[23]Jin, A. and K. Aki, 1989, Spatial and temporal correlation between coda Q^{-1} and seismicity and its physical mechanism, J. Geophys. Res., 94, 14041-14059.
[24]Jin, A. and K. Aki, 1993, Temporal correlation between coda Q^{-1} and seismicity- Evidence for a structural unit in the brittle-ductile transition zone, J. Geodyn., 17, 95-102.
[25Jin, A., C. A. Moya and M. Ando, 2000, Simultaneous determination of site responses and source parameters of small earthquakes along the Atotsugawa fault zone, Central Japan, Bull. Seismol. Soc. Am., 90, in press.
[26]Kanamori, H. and C. R. Allen, 1986, Earthquake repeat time and average stress drop, in Earthquake Source Mechanics, eds. Das et al., Geophys. Mono., 37, M. Ewing Series, Washington, D. C.., 227-235.
[27]Knopoff, L., 1996, The organization of seismicity on fault networks, Proc. Natl, Acad. Sci. USA, 93, 3830-3837.
[28]Li, Y. G., J. E. Vidale, K. Aki and F. Xu, 2000, Depth dependent structure of the Landers fault zone using fault zone trapped waves generated by aftershocks, J. Geophys. Res., 105, 6237-6254.
[29]Li, Y. G., J. E. Vidale, K. Aki, C. J. Marone and W. H. K. Lee, 1994, Fine structure of Landers fault zone: Segmentation and the rupture process, Science, 265, 367-370.
[30]Li, Y. G., K. Aki, J. E. Vidale and F. Xu, 1999, Shallow structure of Landers fault zone using explosion-excited trapped waves, J. Geophys. Res.,104, 20257-20275.
[31]Li, Y. G., K. Aki, J. E. Vidale and M. G. Alvarez, 1998, A delineation of Nojima fault ruptured in the M7.2 Kobe, Japan, earthquake of 1995 using fault zone trapped waves, J. Geophys. Res., 103, 7247-7263.
[32]Li, Y. G., K. Aki, and L. Vernon, 1997, San Jacinto fault zone guided waves: A discrimination for recently active fault strands near Anza, California, J. Geophys. Res., 102, 11689-11701.
[33]Mogi, K., 1969, Relationship between the occurrence of great earthquakes and tectonic structure, Bull. Earthquake Res. Inst. Univ. Tokyo, 47, 429-441.
[34]Ohnaka, M. and L. Shen, 1999, Scaling of the shear rupture process from nucleation to dynamic propagation: Implications of geometric irregularity of the rupturing surface, J. Geophys. Res., 104, 817-844.

[35]Ohnaka, M., 2000, A physical scaling relation between the size of an earthquake and its nucleation zone size, PAGEOPH, 157, in press.
[36]Okubo, P. G. and K. Aki, 1987, Fractal geometry in San Andreas fault system, J. Geophys. Res., 92, 345-355.
[37]Papageorgious, A. S., and K. Aki, 1983, A specific barrier model for the quantitative description of inhomogeneous faulting and the prediction of strong ground motion:
Part I: Description of the model, Bull. Seismol. Soc. Am., 73, 693-721
Part II: Applications of the model, Bull. Seismol. Soc. Am., 73, 953-978.
[38] Papageorgious, A. S., and K. Aki, 1985, Scaling law of far field spectra based on observed parameters of specific barrier model, PAGOPH, 122, 10-24.
[39]Rice, J. R., 1993, Spatial-temporal complexity of slip on a fault, J. Geophys. Res., 98,9885-9907.
[40]Romanowicz, B., 1992, Strike-slip earthquakes on quasi-vertical transcurrent faults: Inferences for general scaling relations, Geophys. Res. Lett. 19, 481-484.
[41]Rydelek, P. A. and I. S. Sacks, 1996, Earthquake slip rise time and rupture propagation: Numerical results of the quantum earthquake model, Bull. Seismol. Soc. Am., 86, 567-574.
[42]Sacks, I. S. and P. A. Rydelek, 1995, Earthquake `Quanta` as an explanation for observed magnitudes and stress drops, Bull. Seismol. Soc. Am., 85, 808-813.
[43]Sato, H. and M. C. Fehler, 1998, Seismic wave propagation and scattering in the heterogeneous Earth, Springer-Verlag New York, Inc. Chap.5.
[44]Scholz, C. H., 1994, A reappraisal of large earthquake scaling, Bull. Seismol. Soc. Am., 84, 215-218.
[45]Scholz, C. H., 1997, Size distribution for large and small earthquakes, Bull. Seismol. Soc. Am., 87, 1074-1077.
[46]Shimazaki, K., 1986, Small and large earthquakes: The effects of the thickness of seismogenic layer and the free surface, in Earthquake Source Mechanics, eds. Das et al., Geophys. Mono., 37, M. Ewing Series, Washington, D. C., 209-216.
[47]Turcotte, D. L., 2000, The physics of earthquakes – is it a statistic problem?, PAGEOPH, 157, in press.
[48]Ward, S. N., 1991, Synthetic seismicity models for the Middle America Trench, J. Geophys. Res. 96, 19800-19810.
[49]Ward, S. N., 1996, A synthetic seismicity model for southern California: Cycles, probabilities, hazards, J. Geophys. Res., 101, 22393-22418.
[50]Ward, S. N., 1997, Dogtails versus rainbows: Synthetic earthquake rupture models as an aid in interpreting geological data, Bull. Seismol. Soc. Am., 87, 1422-1441.
[51]Ward, S. N., 2000, San Francisco Bay area earthquake simulations: A step toward a standard physical earthquake model, Bull. Seismol. Soc. Am., 90, 370-386.
[52]Yoshimoto, K., H. Sato, Y. Iio, H. Ito, T. Ohminato and M. Ohtake, 1998, Frequency-dependent attenuation of high-frequency P and S waves in the upper crust in Western Nagano, Japan, PAGOPH, 153, 489-502.