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Synthesis of Earthquake Science Information and Its Public Transfer: A History of the Southern California Earthquake Center

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Where do we come from?
Where are we?
Where are we going?

Paul Gauguin

1. Introduction

"A natural disaster will hit us at around the time when we forget about the last one" are household words in Japan coined by Torahiko Terada, a physicist, essayist, and leading intellectual of the early 20th-century Japan, who was also one of the founders of the Earthquake Research Institute, Tokyo University. This statement was an effective warning to the public as well as to officials in charge of public safety through the early part of the 20th century, although it did not contain a bit of scientific information about the phenomena causing the disaster. It was effective because everyone agreed with the statement.

On the other hand, a public warning made on a scientific basis that is still controversial may be ineffective and can bring personal disaster to individual scientists involved. An example is the well known story of Omori and Imamura (e.g., Aki, 1980). Imamura believed in a kind of gap theory (Fedotov, 1965) and anticipated a major earthquake in Sagami Bay near Tokyo, which belongs to a belt of major earthquakes, but lacked historical records. He wrote an article in 1906 warning of the lack of fire-preventing facilities in Tokyo and estimating the death of 100 000 by fire when the Sagami Bay earthquake hit the city. This article was criticized severely by Omori as causing social unrest without solid scientific ground. Imamura had a miserable life for 17 y after the publication of the article until the disaster he predicted actually happened in 1923, causing the loss of 140 000 lives. At the time of this great Tokyo earthquake, Omori was attending the second Pan-Pacific Science Congress in Australia. During his return trip by sea, his health declined sharply and he died shortly after arrival in Japan.

The lesson we learn from wise Terada, courageous Imamura, and cautious Omori is that we must build a consensus among scientists for an effective transfer of the earthquake science information to the public, and the consensus must represent the true current status of the scientific community that will not suppress an Imamura's view. Terada's warning had no scientific information, which may have correctly represented the status of the scientific community of his time. Imamura had a specific warning based on his concrete idea about earthquakes, which was rejected by a more prominent scientist of his time. A more sensible message from the scientific community at that time might have been to present Imamura's warning with a likelihood of, say, 50% to the public, because it is supported by one scientist, and opposed by another. This may sound meaningless from the scientific viewpoint, but if the public could have accepted such a warning, with a certain degree of response, the disaster of 1923 might have been reduced significantly. It is not easy to implement such a scheme of information transfer when the science is at a rudimentary stage of development and a small number of scientists are involved in earthquake problems of a given region.

Earthquake science has made a great stride in the last three decades with the plate tectonic revolution, wide acceptance of the fault model, and advances in computer technology. The increasing societal need for mitigating earthquake hazard has also been an important factor for its development. Time has come to find an effective framework through which we integrate all scientific information relevant to earthquakes in a region as a consensus of the scientific community, and present

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it to the public in the region. The Southern California Earthquake Center (SCEC) was founded for this purpose in 1991, as one of the centers of the US National Science Foundation (NSF) Science and Technology Center program.

The first word "synthesis" in the title of this chapter has a more intense meaning than used normally. A traditional way of synthesizing scientific results was, for example, a joint publication of contributions by various authors, like the present Handbook. There is very little interaction among the authors in this form of synthesis. A traditional way of achieving strong interaction among experts on a complex issue has been to form a working group with a task of producing a consensus report. An example is the Working Group on California Earthquake Probabilities organized by the US Geological Survey (USGS). These working groups have limited lifetimes and disappear after completion of the report. SCEC may be considered as a permanent working group addressing the problem of earthquake hazard in Southern California, participated in by scientists of various disciplines who will constantly interact among themselves for consensus building through workshops, seminars, and report writing.

In the present chapter, I shall describe the concept of a "master model," which is proposed as a framework for unifying multidisciplinary observations pertinent to earthquakes in Southern California. A first-generation master model was born in the process of creating a public policy document in response to the public need for knowing the probability of major earthquakes in Southern California after the Landers earthquake of 1992. For a healthy growth of a science, the joy and excitement of doing creative science are as essential as effective public transfer of its product. I shall describe how the concept of a master model served the dual purpose at the SCEC.

2. Master Model Concept as a Framework for Unifying Multidisciplinary Observations on Earthquakes

In May 1989, a workshop was held at Lake Arrowhead, California attended by those who were concerned with seismic hazard in Southern California, and they decided to create SCEC and seek its funding from the Science and Technology Center program of NSF. The University of Southern California (USC) was selected as the host institution for the NSF proposal, and I agreed to serve as the Principal Investigator for the proposal on the condition that T. Henyey would help me in administration and management. During the workshop, a subgroup addressing scientific issues came up with the idea of a "master model," which appears to allow an orderly inclusion of all the research projects proposed by individual participants as its elements. A consensus was quickly developed to put the master model concept as a central idea of the proposal to be submitted to NSF. As such, the master model was a very vague concept when it was born.

One of my long-term dreams has been to develop a model of the Earth's lithosphere in which we predict the occurrence of earthquakes on the basis of the space–time distribution of tectonic stress calculated using various geophysical observables, as the atmospheric scientists forecast weather by computer on the basis of observed pressure, temperature, wind speed, etc. Such a model would have an image of physical concreteness and determinism, and could be described in a straightforward manner in a proposal to NSF. Unfortunately, a proposal along this line was obviously too ambitious and premature, because we do not really know enough about the parameters of material properties and constitutive laws as well as boundary and initial conditions needed to define the problem and it was hopeless to produce anything useful for the public during the lifetime of the center (at most 11 y with three cycles of the evaluation–renewal process) along this line. We called the master model along this line a "physical master model," and I discuss its development at the SCEC later in this chapter.

One thing clear to me at that time was that the master model must be able to absorb all observations pertinent to earthquakes in Southern California. In other words, it must be characterized by parameters that may be effectively constrained by multidisciplinary data including geologic, geodetic, seismological, and historical data on earthquakes in Southern California. After several workshops for preparing the proposal, we recognized the importance of clearly defining the end product expected from the master model. We decided that the end product would be the space–time-dependent probabilities of earthquakes in Southern California and associated ground motions. The master model was defined as a framework through which we should produce this end product by integrating all available information from earth sciences. This scheme is similar to the engineering practice called Probabilistic Seismic Hazard Analysis (PSHA) originated by Cornell (1968) in the western world, but an important difference is that whereas PSHA receives earth science information as given by experts, we generate earth science information by ourselves, and the outcome of PSHA is used to define critical scientific issues to be investigated at the center. Thus, center activities follow a usual scientific cycle of observation, model development, testing the model by comparing predicted with observed seismic hazard, and designing new observations to improve the model. We refer to this model as "hazard master model."

It was easy for me to accept PSHA as a key element of the master model, because I served as the chairman of a panel that evaluated the usefulness of PSHA upon the request of the US National Research Council. Panel members were divided between earth scientists and hazard analysts, and we had to overcome a major disagreement before reaching a consensus report.

The disagreement was concerned with assigning likelihood or probability to the validity of a scientific hypothesis, by procedures that are used by hazard analysts to arrive at a decision needed today, when the data are not sufficient for a unique solution. It was not so difficult for me to accept this because I accepted earlier, in my own seismological studies, the stochastic inverse solution in which a model is considered as a stochastic process. In the end all earth scientist members accepted it as a necessary evil.

In the introduction of this chapter, I suggested that giving 50% probability to the validity of Imamura's prediction might have been more sensible than rejecting it. Here is the essence of the hazard master model. If we know the Earth and earthquakes well enough to construct a physical master model, we do not need the hazard master model. At present we do not have enough facts, though we have competing ideas and hypotheses that will be tested against observations in the long run; but the public needs advice today. The master model approach intends to advance science by model testing with observations and to transfer deliverable information to the public at the same time. We all want to indulge in the joy and excitement of creative science, but it is necessary to deliver our product to the public for continued support of science.

Facing societal problems that require multidisciplinary approaches to their solution, we tend to fault the narrowness of a single scientific discipline. But this very narrowness enabled us to dig deeply into a simplified and isolated problem, leading often to a breakthrough. For example, a PhD thesis that tries to cover a broad area is usually less satisfactory than one that gives a definitive solution to a small problem. We recognized the importance of disciplinary independence in the operation of SCEC in order to keep science alive, and created permanent working groups according to disciplines.

The following eight Working Groups were set up as a balanced representation of the research areas of those interested in participating in the activities of the center:

Group A: Master model and seismic hazard analysis
Group B: Strong ground motion
Group C: Earthquake geology
Group D: Subsurface imaging
Group E: Crustal deformation
Group F: Seismicity and source parameters
Group G: Earthquake physics
Group H: Engineering applications

Although participation in the center activities was open to anyone interested in earthquakes in Southern California, most of the active participants were from universities, government agencies, and private consulting companies in Southern California, for the reason of obvious ease in attending workshops and seminars. This regional limitation of participants was not a problem for Southern California, because we found some of the best scientists in the country in each of the above working groups. This is a direct or indirect inheritance of the long history of excellent earthquake science at the California Institute of Technology (Caltech) Seismological Laboratory, which has been a world center of seismology not only in its disciplinary sense (defined, for example, by Aki and Richards (1980) as a science based on records of seismographs), but also in a broader sense of the physics and geology of earthquakes.

The tasks to be carried out by these working groups for constructing the hazard master model were clear for most groups. Groups C, E, and F would contribute to the characterization of earthquake sources in Southern California, and Groups B, D, and H would contribute in calculating ground motion expected from these sources. Group A would integrate these results into products useful for the public. On the other hand, the role of Group G, earthquake physics, was intended to explore, under the protective umbrella of SCEC, paths toward the physical master model, our ultimate goal.

The proposal to NSF was successful, and SCEC began its activities at the beginning of 1991. It quickly established three data centers, the Seismic Data Center (Caltech, USGS) for waveform data and earthquake parameters; the GPS Data Center [University of California at Los Angeles (UCLA), University of California at San Diego (UCSD), and Massachusetts Institute of Technology (MIT)] for GPS survey data; and the Strong Motion Data Center [University of California at Santa Barbara (UCSB)] for strong motion data.

The funding was nearly equally divided between the infrastructure support and research funding. The infrastructure included the operation of the above three centers, visitors program, expenses for meetings, education and outreach programs required for the NSF centers, and the management of the center.

Research funds were, and still are, distributed in the following manner. The process starts with an Annual Meeting of SCEC, where the tasks to be carried out in the coming year are discussed and decided. Each Working Group then discusses its contribution to the decided tasks, and gives priorities to research areas to be investigated in the coming year. Conclusions from the annual meeting are summarized in the form of RFP (request for proposal) and sent to all SCEC members. Short proposals submitted in response to the RFP are reviewed by leaders of the Working Group for the quality of science, and by the Science Director for the contribution to the SCEC tasks. The funding decision is made by a committee composed of the leaders of the Working Group and the board members who represent the core institutions of SCEC [USC, Caltech, UCLA, UCSB, UCSD, University of California at Santa Cruz (UCSC), Columbia University, and USGS until 1998, and now including California State University at San Diego and University of Nevada at Reno].

The above funding decision process implies a matrix approach made of horizontal lines of tasks and vertical columns of disciplines. The task at the highest level may be the response to a request from the broadest public, and those at lower levels may be in response to more restricted professional and technical user groups. Interactions among different disciplines occur at all levels of tasks, but the more creative, and cutting-edge interactions occur at lower levels, while the consensus-building for public documents is done at higher levels. One may compare the former interaction to the fermentation process and the latter to the distillation, as both processes are needed to produce a fine liquor. The uniqueness of SCEC is this very combination of producing cutting-edge research and passing it along in a timely manner to users.

The Landers earthquake of 1992, the largest earthquake in Southern California since the Kern County earthquake of 1952, occurred in the second year of SCEC, when it had established its working style. Perhaps for the first time in the history of earthquake science, we were ready for a major earthquake, and it occurred just in time. In the next section, I describe how the earthquake helped to pull scientists together to create the first-generation master model for earthquakes in Southern California.

3. The First-Generation Master Model of Earthquake Sources in Southern California

On the morning of 28 June 1992, Southern California was awakened by a very large ($M = 7.3$) earthquake which occurred near the town of Landers, located 30 km north of the San Andreas fault. It was followed by another large one ($M = 6.5$) a few hours later occurring in the Big Bear area 40 km to the west of Landers. People were concerned what this series of earthquakes meant with regard to future earthquakes in Southern California, particularly to the one anticipated on the San Andreas fault, nicknamed the Big One. I felt the need for a quick response to the concerns of the public, and organized a one-day workshop at USC, two weeks after the earthquake, to discuss the implications of these events and SCEC's response. It was attended by SCEC members and key people from the US Geological Survey and the California Department of Conservation's Division of Mines and Geology. It concluded with a decision to produce two reports, Phase 1 and Phase 2. The Phase 1 report would address the short term effects of the Landers–Big Bear sequence on nearby active faults—principally the San Andreas, and the level of ground shaking from potential earthquake scenarios involving the San Andreas fault. The Phase 2 report would extend the study area to the whole of Southern California, and consider the seismic hazard for a longer term. In both reports, the starting point would be the conclusions given earlier in a report entitled "Probabilities of Large Earthquakes Occurring in California on the San Andreas Fault" prepared by the Working Group on California Earthquake Probabilities (WGCEP, 1988).

The Phase 1 report was completed quickly in the fall of 1992, but the Phase 2 report took a long time partly because its innovative nature required a lot of explanation to the broader community of earthquake scientists and to the user community. It was finally published in the April 1995 issue of the *Bulletin of the Seismological Society of America* (WGCER, 1995). The time spent for the completion was, however, not in vain. The ensemble of the model parameters given in the report is now widely accepted as the first-generation master model of earthquakes in Southern California.

The most radical innovation in the report was the use of crustal strain estimated from the GPS data for seismic hazard estimation as proposed by Ward (1994). Southern California was divided into 65 source zones, and the strain accumulating in each zone was translated into seismic moment according to the Kostrov (1974) formula, thus making seismic moment a central parameter of the master model reducible from geologic, geodetic, and seismological data. Since the GPS network in principle can cover the whole of Southern California uniformly, it can give information on earthquake probabilities in the area where geologic information on faults is lacking. The crustal strain estimated from the GPS data showed more diffused pattern than that inferred from geologic data. This comparison stimulated the group of geologists led by D. Schwartz to come up with the consensus parameters of faults in all of the 65 source zones, making the Phase 2 report go beyond the 1988 Working Group report, which was concerned only with the San Andreas and San Jacinto faults. The importance of this extended areal coverage in the report is clearly demonstrated by the Northridge earthquake of 17 January 1994, the most costly (loss of $20 billion) earthquake in the history of United States, which occurred off the San Andreas fault.

The Northridge earthquake was no surprise from the perspective of the Earthquake source model described in the Phase 2 report. The earthquake occurred in a source zone characterized by relatively high earthquake potential, falling in the top 13% of Southern California in terms of moment rate per unit area. While the specific fault had not been known prior to the event, the location, magnitude, and style of earthquake were consistent with our expressed understanding of the regional geology and tectonics.

In order to integrate geologic, geodetic, and seismological data, it was important to classify the 65 source zones into Types A, B, and C according to the availability of these data. Type A zones contained faults for which paleoseismic data sufficed to estimate conditional probabilities of earthquake occurrence in the manner of the 1988 Working Group. We allowed, however, for failure over multiple segments in the form of a "cascade" model, in which the amount of slip is characteristic of a segment, but all earthquakes that can occur by combining contiguous segments are allowed. Type B zones contained faults for which geologists had documented possible characteristic earthquakes but information was insufficient for the conditional probability calculation. For Type C zones, we lacked direct evidence of a preferred characteristic earthquake and we set the seismicity rate to the average of the smoothed catalogue seismicity rate (Kagan and Jackson, 1994) and that corresponding to the geodetic moment rate. By the use of the above classification, we were able to combine existing data from seismology, geology, and geodesy in order to arrive at the preferred model for the whole of Southern California.

Once the preferred model was determined, we could predict the frequency distribution of magnitude for the whole of Southern California. We found that the predicted frequency was about a factor of 2 greater than that observed in the past 150 y. This discrepancy can be explained in the following three ways. First, the seismicity in the past 150 y was anomalously low as compared to the long-term average rate expected from geologic and geodetic data. Secondly, some part of geodetic strain accumulating in the brittle part (assumed to be 11 km thick in this report) may be released aseismically. Thirdly, the maximum magnitude assigned to a source zone using geologic data may be underestimated. All these problems are important from the point of a fundamental understanding of earthquake processes, but we now recognize their importance in practical evaluation of seismic hazard in Southern California and focus our future research on these issues.

Thus, our experience with preparing the Phase 2 report demonstrated all the attributes of the master model, which we described as a framework for integrating multidisciplinary data in the preceding section. Furthermore, the Phase 2 report included the estimation of ground motion and its exceedance probabilities, but was incomplete in this regard because we had neglected the effect of local site conditions on ground motion, which will be the subject of discussion in the next section.

4. Delineation of Local Site Effects on Strong Ground Motion

Once a distinguished earthquake engineer complained to me that engineers read what seismologists write, but seismologists never read what engineers write. So, when I was asked by the geotechnical engineering community to write a review paper on local site effects on strong ground motion, I tried to read papers written on the subject by engineers and engineering seismologists in the United States (e.g., Mohraz, 1976; Seed *et al*., 1976; Trifunac, 1976a,b; Boore *et al*., 1980; Joyner and Boore, 1980) and Japan (e.g., Hayashi *et al*., 1971; Kuribayashi *et al*., 1972; Katayama *et al*., 1978; Kawashima *et al*., 1986). I found remarkably consistent results common to both countries. Soil sites show higher amplification than rock sites for periods longer than about 0.2 sec, while the relation is reversed for shorter periods. This frequency dependence of site amplification is reflected in the site dependence of peak ground motions. Peak ground velocity and displacement show higher amplifications at soil sites than rock sites, while peak ground acceleration is roughly independent of the site classification.

The conclusion of my review (Aki, 1988) was that the above apparent disappearance of site effect at high frequencies is due to the failure of the broad classification (soil vs. rock) of site condition in capturing the essential factor controlling the site effect at high frequencies. A meaningful microzonation is possible for the frequency range, at least, from 1 to 10 Hz, because the geographic variation of site-specific amplification factor varies by a factor of 10, while the standard error of its variation at a given site for different directions of incident waves is less than a factor of 2.

At the time I wrote the above review, there were no systematic studies on the frequency dependence of site effect on weak motions, and it required another review (Aki, 1993) to conclude the difference between weak and strong motion in this respect. The weak motion amplification is higher for soil sites than for rock sites at least up to 12 Hz in California (Su and Aki, 1995), distinctly different from the frequency dependence of strong motion: a clear indication of the pervasiveness of nonlinearity of ground response in earthquake strong motion.

At the time of my review in 1988, I was aware of only one strong motion record demonstrating the unequivocal effect of nonlinearity of soil, namely, the record of the Niigata earthquake of 1964 obtained near a building that failed completely owing to the liquefaction of soil composed of water-saturated sand. There were other cases suggesting nonlinear soil response. For example, strong ground motion observed in Pasadena during the San Fernando earthquake of 1971 by Hudson (1972) did not show any site dependence, while the amplification factor mapped by Gutenberg (1957) using weak motions of small near earthquakes or large distant earthquakes was distinctly higher at soil sites than at rock sites. These examples, however, can be explained by combination of various linear effects, such as frequency-dependent radiation pattern, absorption, impedance, and scattering effects. I agreed, then, with Esteva (1977), who stated that the influence of nonlinearities is often overshadowed by the overall patterns of shock generation and propagation. In other words, the seismological detection of the nonlinear site effect requires a simultaneous understanding of the effects of earthquake source, propagation path and local geologic site conditions.

The Loma Prieta earthquake of 1989 was the first earthquake for which the simultaneous determination of the above three effects was attempted by Chin and Aki (1991), who found that the amplification factor estimated from weak motion overestimates the peak ground acceleration for sites within 50 km from the epicenter. The amount of overestimation appeared to be in the range expected from geotechnical engineering studies. This discovery changed my position with regard to the soil nonlinearity by 180 degrees, and I began to see pervasive nonlinear effects in various seismic observations, as summarized in Aki (1993).

This change in my position was reflected in SCEC's relation with the geotechnical engineering community. The seismological community has been skeptical about the nonlinear effect (which reduces the estimate of ground acceleration) claimed by the geotechnical engineers primarily on the basis of experiments on small soil samples in the laboratory. There has been very little interaction between the two communities because of the diametrically opposed difference on this most fundamental issue on the site effect. Because of my acceptance of nonlinearity, it was easy for SCEC to have a smooth cooperation between the two disciplines from its inception. We also found, especially through many observations made during the Northridge earthquake of 1994, that the site effect is a much more complicated problem than seismologists used to think, and certainly deserves such a cooperative research. For example, a timely and ingenious deployment of dense seismograph networks by a UCLA group (Gao *et al*., 1996) after the earthquake revealed that the concentration of damage in Santa Monica was not due to site conditions at shallow depths normally concerned by geotechnical engineers, but to a wave focusing effect by a geologic structure at greater depth. The Phase 3 report, currently under preparation under the leadership of N. Abrahmson, is intended to include the consensus on site effects, in addition to the updates of earthquake source characterization given in the Phase 2 report.

5. Toward a Physical Master Model of Earthquakes like that Used for Weather Forecasting by Computer

As mentioned in an earlier section, we wanted to develop at SCEC a physical master model, a model of the Earth's lithosphere in which we could predict the occurrence of earthquakes based on the space–time distribution of tectonic stress calculated using various geophysical observables as the atmospheric scientists forecast weather by computer, based on observed pressure, temperature, wind speed, etc. For practical reasons, however, we took the approach of a hazard master model that unified observations in the end product, namely, PSHA.

Our practical approach based on PSHA tried to include all accomplishments of earthquake science made in the past three decades on the basis of plate tectonics and the fault model of earthquakes. The concept of seismic moment unified the geologic, geodetic, and seismological data under the constraint from plate tectonics (Aki, 1966; Brune, 1968; and Kostrov, 1974). The concept of characteristic earthquake introduced by Schwartz and Coppersmith (1984) from paleoseismological observations played a major role in translating observed fault parameters, such as the slip rate, amount of slip, and style of fault into earthquake probabilities. The concept of "cascade" was introduced by D. Jackson into the SCEC Phase 2 report to allow a less restrictive characteristic earthquake model.

The closest thing to what I had in mind as a physical master model for Southern California came from the work by Bird and Kong (1994), done outside of SCEC activities. Their model consisted of a brittle upper crust and a ductile lower crust. Their upper crust model includes all faults with annual slip greater than 1 mm. The deformation of the upper crust is governed by frictional rheology containing a pore pressure effect and specified by different coefficients of friction on the fault and off the fault. The deformation of the lower crust follows the dislocation creep law with the temperature dependence parametrized by the activation energy. The subsurface temperature was estimated from the heat flow at the surface. The boundary condition is given by a standard global model of plate motion. The data to fit with the model are long-term fault slip rates measured geologically, trilateration and very-long-baseline radio interferometry data, and stress orientations from focal mechanisms and *in situ* measurements. The coefficient of friction of the upper crust and the activation energy of the lower crust were free parameters, and they concluded that the coefficients of friction for faults is as low as 0.17, and that a lower activation energy improves the model fit. However, they concluded that the disagreement between the observed fault slip rate and the predicted rate by the best fitting model is too large to allow use of the computer model for practical purposes of seismic hazard estimation. Furthermore, the model of Bird and Kong (1994) was intended for studying a long-term (order of 1000 y) behavior of the Earth's crust, while SCEC is interested in the behavior on shorter time scales.

Rock friction behavior in the time scale of interest to SCEC has been systematically studied in laboratory experiments by Dieterich (1972, 1979, 1981), with results generalized in the form of a rate- and state-dependent friction law by Ruina (1983). This law includes a characteristic slip distance L for evolution of surface state and slip weakening. In other words, there is a unique length scale associated with a fault governed by this law specified by a given set of parameters. This length scale unique to a given fault must play a fundamental role in creating the characteristic slip that should repeatedly occur according to the characteristic earthquake model. The SCEC Working Group G (Earthquake Physics) addressed this fundamental problem from the start. For example, Rice (1993) analyzed a 3D static problem of a vertical fault governed by the rate- and state-dependent friction law by discretizing equations involved with the cell size h. He found that the simulated slip shows spatiotemporal complexity when h is greater than a critical size h^*, called "nucleation size," that scales with the characteristic slip distance L. When h is less than h^*, the complexity disappears in favor of simple periodically repeated large earthquakes, namely, the characteristic earthquake. This conclusion highlights the importance of length scale unique to a fault for our goal of constructing a computer model of earthquakes.

Another fundamental contribution from SCEC to the fault-specific length scale is an unequivocal confirmation of the existence of seismic guided waves trapped in the fault zone of the Landers earthquake of 1992 by Li *et al*. (1994), who estimated a fault zone width of about 200 m, with shear velocity of 2.0–2.2 km sec^{-1} and Q of about 50 by comparing the observed waveform with the synthetic one. This size of the fault width is consistent with the size of breakdown zone (comparable to the nucleation size mentioned above) estimated by Papageorgiou and Aki (1983) from the upper cutoff frequency (source-controlled $f_{\max}$) of strong motion acceleration spectra for several major earthquakes in California.

Interestingly, a similar estimate of the width of the Landers earthquake fault zone was made by an entirely different method. From a detailed study of tension cracks on the surface, Johnson *et al*. (1994) concluded that the Landers fault rupture was not a distinct slip across a fault plane but a belt of localized shearing spread over a width of 50–200 m. They suggested that this might be a common structure of an earthquake fault, which might have been unrecognized previously because the shearing is small and surficial material is usually not as brittle as in the Landers area. We identify this shear zone with the low-velocity, low-Q zone found from the trapped modes because they occur exactly at the same place. Since the trapped modes were observed from aftershocks with focal depths greater than 10 km, we conclude that the shear zone found by Johnson *et al*. (1994) extends to the same depth.

Repeated measurements of fault-zone trapped waves using artificial sources by Li *et al*. (1998) led to the first discovery of fault healing by a controlled field experiment. The travel times for identical shot–receiver pairs decreased by 0.5–1.5% from 1994 to 1996, with the larger changes at stations closer to the fault zone. These observations indicated that the fault strengthened after the main shock, most likely owing to the closure of cracks that were opened by the 1992 earthquake. In the past, indirect evidence such as time-dependent variations in source properties of repeating earthquakes (Marone *et al*., 1995) showed some consistency to the healing predicted by the rate- and state-dependent friction law. The new discovery from the trapped mode offers direct evidence for a rather broad fault zone associated with the Landers earthquake. The observation of the fault-zone trapped mode will enable direct estimation of the friction law parameters, serving as a link between the laboratory and the field.

Suppose we have a model of Southern California with fault zones delineated in 3D and characterized by a friction law with known parameters; we need to know how this model is loaded. Some researchers assign the loading at the periphery of the model as the displacement given by the global plate motion, and others give it as a drag exerted on the brittle part of the lithoshere by the deformation in its ductile part. Castle and Gilmore (1992), for example, found that recent major earthquakes in Southern California are located in the zone of steep lateral gradient in uplift, and hypothesized a localized creep below the zone of steep gradient along the detachment surface between the brittle and ductile part of the lithosphere. The GPS network, currently expanding in Southern California, will give improved information on this matter. The abundantly and easily available seismic information on coda waves of local earthquakes may also be useful for estimating the localized creep, because the observed correlation between coda Q and seismicity has been interpreted by a model of creep along the brittle–ductile boundary (Jin and Aki, 1989, 1993), and there is an indication of low coda Q (Ouyang, 1997) along the zones of steep gradient in uplift found by Castle and Gilmore (1992). In this regard, Aki and Ferrazzini (2000) have found a more powerful method of coda analysis than the traditional coda Q measurement for mapping localized heterogeneities from observations at the Piton de la Fournaise volcano on the Reunion island in the Indian Ocean. The new method appears to give better correlation with the creeping zone geodetically assessed by Castle and Gilmore (1992) when applied to Southern California (A. Jin, personal communication), offering a promising way of studying deformation in the brittle–ductile transition zones in an earthquake region.

When we combine Rice's (1993) analysis based on the rate and state-dependent friction law with the fault zone width estimated from field observations for the Landers earthquake by Li *et al*. (1994, 1998), we will be able to generate a large characteristic earthquake, but unable to generate smaller earthquakes, which were abundantly observed as aftershocks and background seismicity of the region. Among what are missing in Rice's analysis, the following three elements stand out: (1) dynamics of rupture that may produce nonuniform slip and stress roughening on the fault plane; (2) preexisting irregular geometry of the fault, such as segmentation and branching; and (3) preexisting inhomogeneity in the frictional properties including pore fluid distribution.

The contribution from earthquakes other than characteristic earthquakes to seismic hazard was important in Southern California as described in the Phase 2 report, and our physical master model must somehow account for them if it ever is to replace the hazard master model. The only way to include the above three elements into our physical model would be via a stochastic approach, because their detailed specification in any deterministic manner would be impossible now. Thus, our strategy for constructing the physical master model will be separated into a deterministic part dealing with characteristic earthquakes, and a stochastic part dealing with non-characteristic earthquakes. For the deterministic part, the tomographic monitoring of fault zones by trapped mode observation and the monitoring of the loading process at the brittle–ductile transition zone by the geodetic and seismic observations will supply basic parameters of the physical master model to be used in computer simulation. For the stochastic part, we may learn from the approaches taken by atmospheric scientists in dealing with effects of land surface heterogeneity that spans a wide range of scales. Giorgi and Avissar (1997) reviewed recent studies in this subject area, and suggest that these approaches may be applicable to earthquake faults with inhomogeneous frictional strength, surface roughness, porosity, and permeability that vary across a variety of length scales.

6. Transportability of the Master Model Concept to Other Regions of the World

It is true that the SCEC was possible because of the funding from the federal and local governments and other sources available in the United States, and also because of the scientific manpower available in Southern California. The concept of a master model, however, can be useful for any region with any available funding and manpower. An example is early 20th-century Japan as discussed in the introduction. If we had had a master model including Imamura's hypothesis, and had assigned a certain likelihood to his assessment of damage, and if the government official in charge of the disaster mitigation had accepted it as a consensus from the scientific community, the loss of lives in 1923 might have been reduced significantly. At present, there are many earthquake countries where only a few Imamuras exist. They can apply the master model concept by searching for all the theories and models applicable to their region and taking advantage of the knowledge about them accumulated worldwide.

The advantage of the master model concept comes from the fact that model construction may not be as expensive and time-consuming as data gathering. As mentioned earlier, the construction of the first-generation master model for Southern California was possible only after we divided the region into zones A, B, and C according to the availability of data, adopting different ways of using available data for different zones. As the data gathering proceeds, some of the C zones will be upgraded to B zones, and some of the B zones to A zones. Since the public needs advice today, we must accept the existing data and make the best use of it. This, however, should not be used as an excuse for quitting the data gathering, which is essential for the advancement of science. Keeping a proper balance between the data gathering and model construction is an important part of the master model maintenance, as explained earlier using the SCEC example.

The concept of the master model, however, will be most productive in countries with past extensive developments in earthquake studies, such as Japan, where the emphasis has been placed on multidisciplinary data gathering without much effort in synthesizing the data as a consensus of the research community. The master model concept will help to develop a quantitative model integrating the data from historical and instrumental seismology, geodesy, and geology, in the manner of the SCEC example. The model will not only give consensus and up-to-date policy documents needed by the public, but also help the scientific community to identify the focus of future research, as the SCEC identified the three most important issues for earthquakes in Southern California, namely, (1) the maximum magnitude expected in a region, (2) the fraction of aseismic strain in geodetically determined deformation, and (3) significance of the long-term change in seismic activity of a region. These issues have been discussed in Japan by individual scientists, but never brought out as a consensus focus of future study by the scientific community. Consensus building among scientists using the master model approach will quench the futile controversies that have been going on among scientists in Japan regarding earthquake prediction research. Earthquake prediction research in Japan has traditionally not included the component of strong ground motion prediction and consequently Japan has not developed a well-established bridge between the community of earthquake engineers and that of scientists, despite the effort of those working in the interface. The situation in the United States has been similar to that in Japan, but we saw some improvement at the SCEC as explained earlier.

The ability to reach a true consensus is a strength of a community, and the inability is a weakness. If the scientific community is divided, nonscientists will take the lead in research and may kill science eventually. As explained in the SCEC example, the master model concept will avoid such a disaster, giving the leadership to scientists in doing the best in creative science and, at the same time, giving the best to the public.

7. Conclusion

The SCEC successfully developed a new concept called "master model" for earthquakes in Southern California, which functions as a framework for integrating all multidisciplinary data on earthquakes in Southern California. The first-generation master model was constructed in response to the public's need for information on future earthquakes in Southern California after the Landers earthquake of 1992. It not only gave the public a consensus view of the scientific community on future earthquakes in Southern California, but also stimulated creative science through vigorous interactions among various disciplines involved in earthquake studies. The first-generation master model unifies the multidisciplinary data through its end product, namely, the PSHA (Probabilistic Seismic Hazard Analysis). Our ultimate goal, however, is to unify the data through a physical model of the Earth's lithosphere containing seismogenic faults. The SCEC made some progress toward this goal of constructing a "physical master model" both theoretically and observationally. The discovery of seismic guided waves trapped in the fault zone of the Landers earthquake of 1992 and the temporal change in their properties associated with possible healing of the fault measured in repeated controlled experiments will offer a field estimation of the parameters of the rate- and state-dependent friction law, which can be used to develop a computer model of earthquake occurrence relevant to the time scale of interest to SCEC. This deterministic approach may be used for simulating the characteristic earthquake, while noncharacteristic earthquakes may require a stochastic approach for simulation. Thus, the master model approach stimulates the cutting edge research for earthquake science. Furthermore, it is highly transportable to developing countries, where the funding and manpower for research are lacking, because a master model can make use of plausible hypotheses that may compensate for the lack of data. It is, however, most effective for countries where extensive data gathering has been done but little has been done in their synthesis for public use and for the sake of science itself.

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The idea of forming a center for earthquake research in Southern California was first discussed at a dinner table among Jim Dieterich, Lynn Sykes, Rob Wesson, and myself during the US–Japan earthquake prediction conference at Morro Bay, California in the fall of 1988. After my initial call for a meeting to create the center failed, Ralph Archuleta, Bill Stuart, and I composed an appeal for the center, and circulated it at the AGU fall 1988 meeting in San Francisco. Rob Wesson's persuasion as the chief of the USGS Office of Earthquakes finally succeeded in organizing the Lake Arrowhead workshop in May, 1989 as mentioned in the text. During the Lake Arrowhead workshop, the name "Southern California Earthquake Research Center" was initially proposed, but Brian Tucker insisted that we drop the word "Research" from it. This turned out to be an extremely important decision as it expressed our commitment to everything about earthquakes in Southern California, including outreach and education. For two years before the official inception of SCEC, Leon Knopoff and I organized monthly seminars on earthquake prediction in which future SCEC members participated. This helped a quick development of cooperation among the members after the official start of SCEC in the beginning of 1991.

During the first site visit by NSF/USGS in 1990 a diagram of the master model drawn by Bernard Minster was used in every presentation. He served as the vice chairman of the SCEC Board and, among other things, made smooth and complete the transition to the new leadership of Tom Henyey (Center Director) and Dave Jackson (Science Director) after my resignation as Science Director in 1996.

In the workshop held two weeks after the Landers earthquake, strong opposition to the Phase 2 report was expressed by some, who felt that the Phase 1 report, a more traditional public document by scientists in response to an earthquake, was enough. Dave Jackson supported the Phase 2 vigorously, and took leadership in consensus building and writing.

Geoff Martin organized several workshops in which we explained the Phase 2 report to potential users. The subsequent wide acceptance of the report is due largely to his effort. The Advisory Council to SCEC went beyond mere advising, and participated in the growth of SCEC. Its insistence on the need for strategic planning led to the task-discipline matrix approach mentioned earlier. The Council was chaired by Barbara Romanowicz in the formative years of SCEC, who was then succeeded by John Rundle. Its members were C.B. Crouse, Jim Davis, Jim Dieterich, Paul Flores, I.M. Idriss, Tom Jordan, Shirley Mattingly, Dennis Mileti, Bill Petak, Kaye Shedlock, Bob Smith, Cheryl Tateishi, and Susan Tubessing.

Bill Petak used to tell me that "SCEC is a miracle," watching many people gathered at various SCEC meetings, who competed with each other in the past but now cooperate. The miracle occurred thanks to three incredibly timely earthquakes. The Loma Prieta earthquake of 1989 occurred at the time when the original SCEC proposal was being reviewed at NSF. The Landers earthquake of 1992, in the second year of SCEC, pulled the researchers together to develop the first-generation master model, just in time for the first renewal proposal to NSF. Finally, shortly after the Northridge earthquake of 1994, NSF notified us that the funding increase requested in our renewal proposal was approved. The last earthquake also justified our research focus given to the Los Angeles basin rather than the San Andreas fault.

Important decisions at SCEC were made by the Steering Committee, composed of the Board members representing core institutions (Kei Aki, Ralph Archuleta, Rob Clayton, Tom Heaton, Dave Jackson, Karen McNally, Bernard Minster, Jim Mori, Nano Seeber), the Working Group leaders (Duncan Agnew, Kei Aki, Ralph Archuleta, Rob Clayton, Steven Day, Egill Hauksson, Dave Jackson, Leon Knopoff, Geoff Martin, Kerry Sieh), Executive Director (Tom Henyey), Director for Knowledge Transfer (Jill Andrews), Director for Education (Curt Abdouch), and Director for Administration (John McRaney). The last four mentioned above have formed the core of the SCEC operation, implementing the decisions made by the Steering Committee to run a highly complicated organization.

Last but not least, Jim Whitcomb served as the NSF program director for SCEC.

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