Review:

Earthquake Observation and Strong Motion Seismology in Japan from 1975 to 2005

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We review earthquake observation and strong motion seismology in Japan over the three decades starting in 1975. Preceding the 1995 Kobe earthquake, earthquake prediction research programs played an important role in earthquake observation research. The devastating damage from this earthquake, however, forced a change in emphasis from empirical short-term prediction to long-term forecasting of earthquakes and the prediction of strong ground motion. Nationwide observation networks were set up, and progress in strong motion seismology was applied to projects of national seismic hazard maps. The next disastrous earthquake may even force their reexamination in the near future.

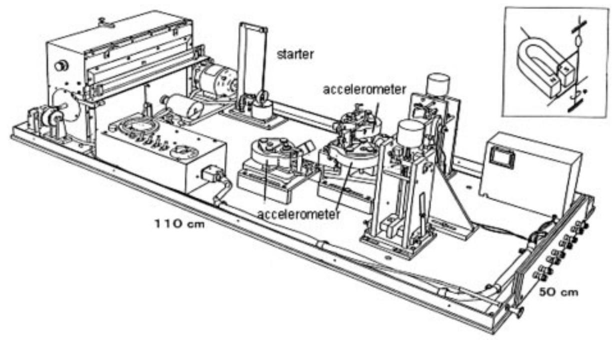

Fig. 1. USCGS strong motion seismograph (source: http://www.k-net.bosai.go.jp/KYOUKAN/ayumi/ayu2.htm).

Keywords: earthquake observation, strong motion seismology, nationwide observation network, earthquake prediction research, seismic hazard map

1. Introduction

The 1923 Kanto earthquake with a magnitude (M) of 7.9 is one of the most devastating in Japanese history, costing over 105,000 lives, and totally destroying more than 109,000 houses. This earthquake also triggered the establishment of the Earthquake Research Institute (ERI) at the University of Tokyo directed by Engineering Professor Kyoji Suyehiro. The ERI was the first research group formed to study both earthquake and strong motion (engineering) seismology [1]. Mishio Ishimoto, the second director, invented a short-period accerelograph in 1931.

Meanwhile, in the United Sates (US), John R. Freeman became interested in strong motion seismology and earthquake engineering based on his experience in the 1925 Santa Barbara earthquake and his meeting with Suyehiro at the 1929 World Engineering Congress [1]. He strongly recommended to the US Secretary of Commerce that an instrument for recording strong motion be designed and built. Freeman also stimulated early interactions between US and Japanese institutions in the field of strong motion (engineering) seismology [2]. Suyehiro was invited to the US by the American Society of Civil Engineers (ASCE) in 1931. In his lectures there, he used the term "engineering seismology" for the first time in the history of seismology, focusing on the importance of directly measuring strong ground acceleration to collect data for developing effective design of earthquake-resistant structures [3].

Along with Freeman's lobbying efforts, the advocacy of Suyehiro helped the US Coast and Geodetic Survey (USCGS) become authorized to develop and install strong motion seismographs, the first of which were installed in late 1932 in time to record strong ground motions from the 1933 Long Beach earthquake [1] (**Fig. 1**). This was the actual beginning of modern strong-motion seismology.

As mentioned above, the 1923 Kanto earthquake indirectly initiated strong motion (engineering) seismology and strong motion instrumentation. So, Tatsuo Usami, who had worked for the ERI, started his review in 1974 with an overview of this earthquake [4]. He also reviewed the earthquake prediction system in Japan from its "blue print" to 1974. We follow this paper with a review of earthquake observation and strong motion seismology in Japan for the three decades immediately following the period covered by Usami's paper [4].

In reviewing seismology in Japan, we will focus on regional rather than global seismology. The devastating 1995 M7.3 Kobe (Hyogo-ken Nanbu) earthquake exerted such a great impact on Japanese seismologists that the seismology itself was forced to change in Japan. We will first review earthquake observation and strong motion seismology preceding the 1995 Kobe earthquake, then that after the earthquake.

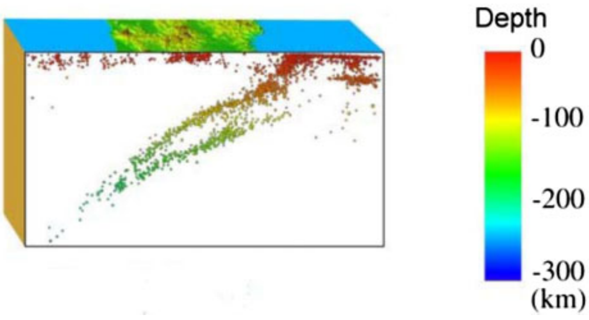

Fig. 2. Double-planed deep seismic zone in the Tohoku region, northeastern Japan (source: http://www.hp1039.jishin.go.jp/eqchr/figures/f4-3.jpg).

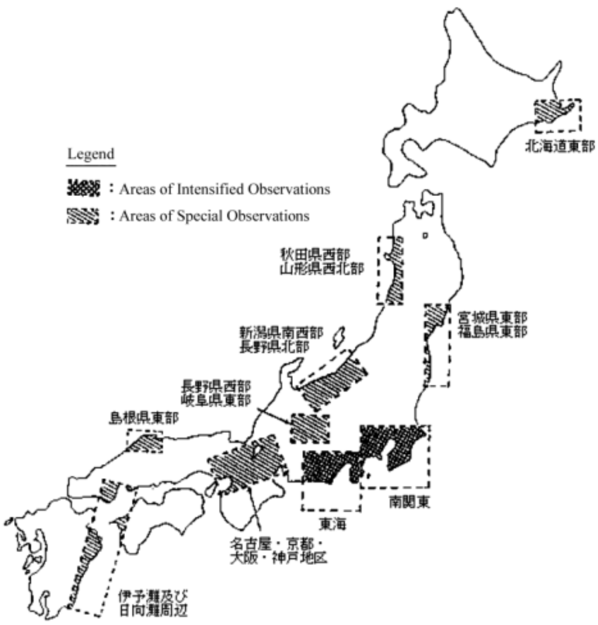

Fig. 3. The original map in Japanese with the Areas of Intensified Observations and Areas of Special Observations designated by CCEP in 1978. Southern Kanto (南関東) and Tokai (東海) are Areas of Intensified Observations [10].

2. Earthquake Observation Preceding 1995

Earthquake observation in Japan depended strongly on national earthquake prediction research programs preceding the 1995 Kobe earthquake. Usami [4] already reviewed the first and second programs and a proposal called the "blue print" [5], so we will start by reviewing the third and later programs by summarizing their history as outlined by Naoshi Hirata [6].

The third five-year program from 1974 to 1978 promoted new observation, including seismic observation telemetry, deep borehole measurement, cabled ocean bottom seismographs, and buried volumetric strainmeters [7]. Seismic network telemetry improved microearthquake detectability and hypocenter determination accuracy, uncovering the double-planed structure of deep seismic zones in the Kanto and Tohoku regions, northeastern Japan [8] (**Fig. 2**).

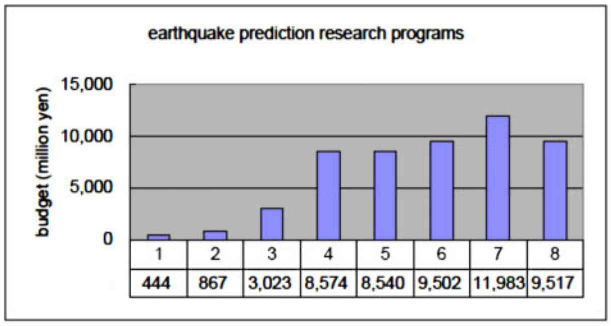

Fig. 4. Budget in million yen allocated for the earthquake prediction research programs at national universities of Japan. The program 8 denotes the first new program (source: http://www.mext.go.jp/b_menu/shingi/gijyutu/gijyutu6/toushin/07011910/001.pdf).

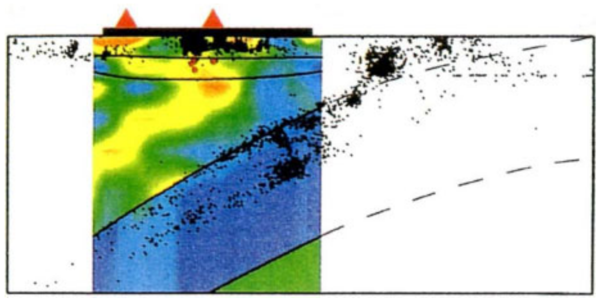

Fig. 5. Cross section of the S-wave velocity structure, and the distribution of earthquakes (black dots) and volcanoes (red triangles) in the Tohoku region, northeastern Japan [14].

The Coordinating Committee for Earthquake Prediction (CCEP) designated Southern Kanto an Area of Intensified Observation, and eight other zones as Areas of Special Observations in 1970. Tokai was changed from an Area of Special Observation to an Area of Intensified Observation in 1974 (Fig. 2 of [4]). Thus, efforts to improve earthquake prediction focused on these two Areas of Intensified Observations. Prominent seismic activity from 1974 in and around the Izu peninsula in this area prompted the Geodesy Council to recommend strengthening of the third program in 1975. Marked foreshocks and precursory anomalies in crustal strain, groundwater radon concentration, and underground water level were observed by strengthened observation networks, preceding the 1978 Izu-Oshima-kinkai earthquake.

In 1976, Katsuhiko Ishibashi proposed the "Tokai earthquake hypothesis," that a large earthquake would soon occur in the Tokai area and its focal zone was likely to extend deep into the Suruga bay [9]. Based on this proposal and studies by Kiyoo Mogi and others, the Geodesy Council recommended further strengthening of the third program in December 1976. The "Prediction Council for the Tokai Area" was then established in the CCEP in 1977, and the CCEP itself reorganized the Areas of Special Observations in 1978 (**Fig. 3**).

As another result of Ishibashi's proposal, the "Large-scale Earthquake Countermeasures Act" went into effect in 1978. The Central Council for Disaster Prevention designated areas surrounding the source region of the hypothetical Tokai earthquake as "Areas under Intensified Measures against Earthquake Disaster" defined in this act. The Prediction Council for the Tokai Area in the CCEP was replaced by the "Prediction Council for Areas under Intensified Measures against Earthquake Disaster" at the Japan Meteorological Agency in 1979.

The Large-scale Earthquake Countermeasures Act also promoted the national earthquake prediction research program, so the budget for research at national universities roughly tripled from 1979 to 1983 (**Fig. 4**). This fourth five-year program enhanced a combination of long- and short-term prediction [7]. The "place" and "magnitude" of a future earthquake are sought using the methods of long-term prediction, while the "time" of the earthquake is sought with the methods of short-term prediction by detecting precursor phenomena and understanding what is really going on preceding the earthquake. Certain progress was made in measuring strain distribution in the Japanese islands, data exchange among microearthquake observation networks, automatic seismic data processing, and cabled ocean bottom seismographs.

The fifth five-year program from 1984 to 1988 further improved the observation research mainly in the Areas for Intensified Observations, i.e., Southern Kanto and Tokai, and the Areas of Special Observations [11]. Based on the idea of the long- and short-term prediction, a variety of observations with improved quality and density as well as comprehensive analyses of precursory data from various viewpoints were made during this period.

In the sixth five-year program from 1989 to 1993, basic research on inland earthquakes was initiated, because little was known about how earthquakes away from plate boundaries were generated [11]. Large-scale seismic tomography was conducted using data from high-sensitivity seismic networks developed in the national earthquake prediction research programs. Results showed a tectonic-scale correlation between three-dimensional seismic velocity structures and seismogenic structures such as thermal structures [12] (**Fig. 5**). The detailed velocity structure on a scale comparable to a seismogenic fault became a target of the study. The source region of the 1984 Nagano-ken Seibu earthquake was studied during the fifth and sixth programs. This was the first joint observation for inland earthquakes by many institutions with modern instruments. Some relationships were obtained among the heterogeneous structures of seismic velocity and electrical resistivity and the distribution of microearthquakes [13].

Space-based technology, such as the Global Positioning System (GPS) and Interferometric Synthetic Aperture Radar (InSAR), has become an important tool in seismology and earthquake prediction research, since the first experimental satellite was launched for the GPS in 1978. The Geographical Survey Institute of Japan (GSI) began installing a network of GPS receivers in 1990 that has enabled continuous monitoring of crustal deformation in the Japanese islands highly accurately.

Fig. 6. SMAC-A strong motion seismograph (source: http://www.k-net.bosai.go.jp/KYOUKAN/ayumi/ayu5.htm).

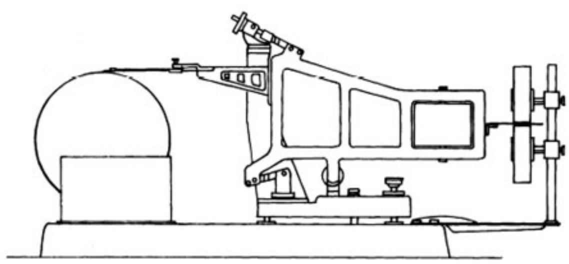

Fig. 7. Horizontal component of the JMA strong motion seismograph, Model 50 [17].

3. Strong Motion Seismology Preceding 1995

Usami did not review strong motion (engineering) seismology [4], but Kazuyoshi Kudo, who was previously working for the ERI, reported progress of engineering seismology in Japan in 1993 [15]. He reviewed this discipline for the four decades from 1950, so we will also review strong motion seismology in Japan from the 1950s by summarizing his report.

According to Suyehiro's advocacy mentioned earlier [3], most strong motion seismographs include built-in accerelographs, but the accerelograph that Ishimoto produced in 1931 is not called a strong motion seismograph. Strong motion seismographs should, as their name indicates, record strong ground motion alone, not weak ground motion, necessitating a trigger system. The USCGS strong motion seismograph has a "starter" as a mechanical trigger (**Fig. 1**). The 1948 Fukui earthquake motivated members of the Strong Motion Accelerometer Committee (SMAC). They designed the first Japanese strong motion seismograph with a starter, which is called a SMAC-A seismograph (**Fig. 6**), in 1953 [16]. The Japan Meteorological Agency (JMA) designed a low-gain displacement seismograph, Model 50, with a starter in 1950. This is also called an "ichi-bai" strong motion seismograph in Japanese (**Fig. 7**).

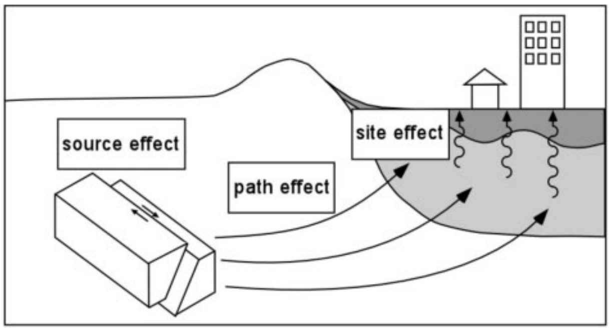

Fig. 8. Three factors effective on strong ground motion.

Modern strong motion seismology was initiated in Japan in the early 1950s, accompanying the development and installation of these strong motion seismographs. Strong ground motion is considered to result from three factors that are source, path, and site effects (**Fig. 8**). For strong motion prediction, which is a goal of strong motion seismology, we must study these effects intensively to form seismic hazard maps. The first attempt at such mapping, the Kawasumi map [18] was made in 1951 using empirical attenuation relations and statistical analyses of data from historical documents. Even in the 1950s, the site effect was studied physically ("Kanai equations" [19]). These studies and observations with the strong motion seismographs founded strong motion seismology preceding 1995.

In the 1960s, SMAC seismographs deployed nationwide observed significant strong ground motions from the 1962 Hiroo-oki, 1964 Niigata and 1968 Tokachi-oki earthquakes, and the Matsushiro earthquake swarm. The relationship between high accelerations and damage was discussed using these records. Long-period ground motion was first observed in Japan during the Niigata and Tokachi-oki earthquakes. The site effect was further studied using multiple reflection theory, borehole observations, and shallow S-wave velocity explorations.

Large-scale structures such as high-rise buildings, long-span bridges, and large oil storage tanks began to be built in the 1970s. Accordingly, more attention was paid to the long-period ground motions and deeper velocity structures, so that the path effect beyond empirical attenuation and Q began to be studied. The "seismic basement" was defined as the uppermost part of the crust, and large-scale explorations were conducted in sedimentary basins [20]. The source effect also began being studied in the 1970s with the introduction of dislocation source and source fault models.

Study on the source effect was further expanded to complex rupture processes and the empirical or statistical Green's function method in the 1980s [20]. For the path effect, more realistic velocity structures were explored and used in strong motion prediction in which theoretical long-period ground motions were computed based on numerical schemes [22]. JMA strong motion seismographs were renewed from Model 50 to Model 87 with digital recording in 1987.

4. Earthquake Observation After 1995

In 1994, the seventh five-year program started targeting the evaluation of earthquake potential in addition to the methods of the long- and short-term prediction [11]. Attempts were made to identify present moment in relation to a regional earthquake cycle. The budget for national universities had by then increased to about 12 billion yen (**Fig. 4**). The 1995 Kobe (Hyogo-ken Nanbu) earthquake occurred during this seventh program, killing 6,434 people and completely destroying 104,906 houses. Since this earthquake was as devastating as the 1923 Kanto earthquake and no prediction had been issued in advance, public opinion called for changes in the direction of earthquake prediction research from short-term earthquake prediction to an understanding of the earthquake generation mechanism for scientific development. The new program of the earthquake prediction research emphasized monitoring, modeling, and simulation to understand earthquake sources and their surrounding environment [23].

The "hypothesis of persistent asperities" was introduced into the "asperity model" during this new program [24]. It was assumed in the model that there exist characteristic sites for asperities where large fault slip occurs only as a seismic event, and that the individual asperities usually manifest magnitude 7 earthquakes but sometimes synchronize to cause magnitude 8 earthquakes. The asperity model can explain the repeatability of large plate-boundary earthquakes and be used for predicting the spatio-temporal pattern of tectonic stress due to plate-driving forces preparing for the earthquakes. Most studies of the new earthquake prediction research programs were performed in the direction of this asperity model [6].

The 1995 Kobe earthquake also brought home the importance of national earthquake disaster prevention measures. Following on the lessons learned from the great Hanshin-Awaji earthquake disaster caused by this earthquake, the Headquarters for Earthquake Research Promotion (HERP) was established in July 1995 as a governmental decision making organization (**Fig. 9**). The Headquarters consists of Policy and Earthquake Research Committees for promoting a comprehensive national policy on earthquake disaster prevention, establishing "National Seismic Hazard Maps for Japan" as a major area of investigation on earthquakes for strengthening disaster prevention [25].

In 1997, the Headquarters for Earthquake Research Promotion released plans for comprehensive surveys and observation to set up high-sensitivity seismographs, broadband seismographs, strong motion seismographs, and continuous GPS observation facilities for earthquake researches. Active fault surveys are planned for long-term evaluation. Based on these plans, nationwide dense observation networks such as Hi-net (high-sensitivity seismographs), F-net (broadband seismographs), and K-NET and KiK-net (strong motion seismographs) operated by the National Research Institute for Earth Science and Dis-

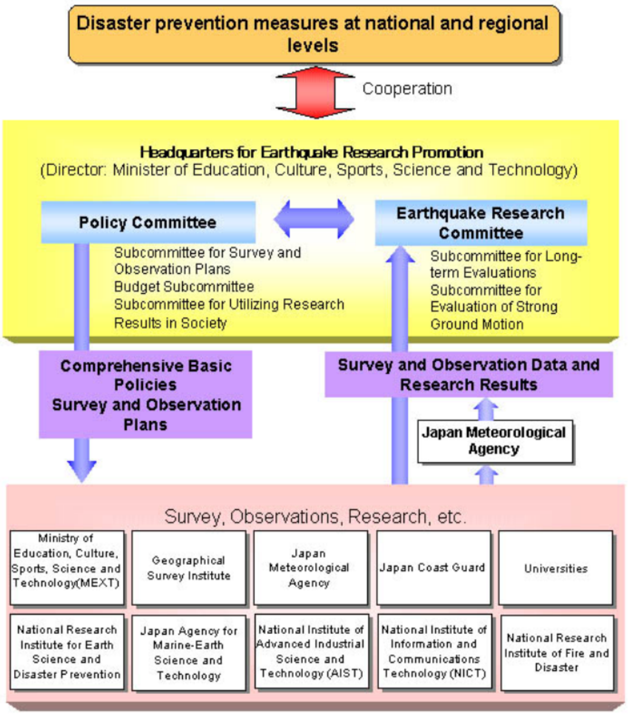

Fig. 9. The structure of the Headquarters for Earthquake Research Promotion (from http://www.jishin.go.jp/main/w_30_f-e.htm).

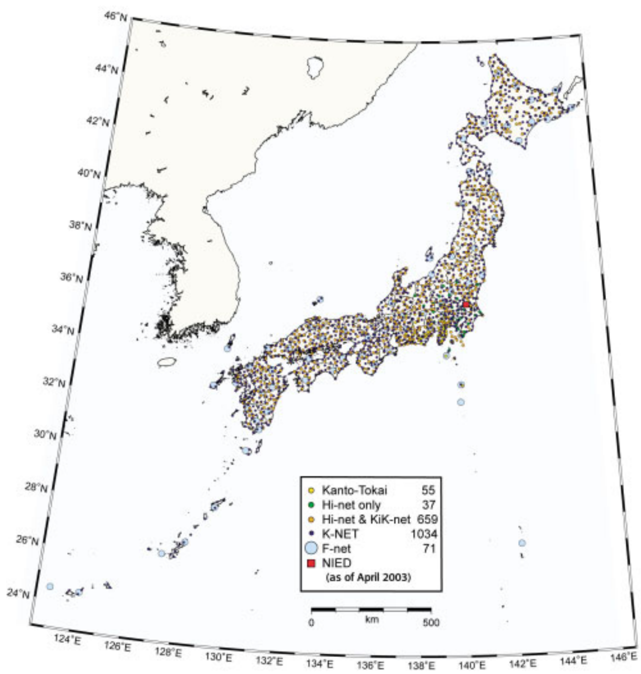

Fig. 10. Distribution of seismic stations operated by NIED as of April 2003 [26].

aster Prevention (NIED) and GEONET (GPS network) by the GSI were implemented or strengthened (**Figs. 10**, **11**) [26, 27]. The JMA and universities collaborated in providing data open to the public. As a result, continuous observation succeeded in capturing new signals from

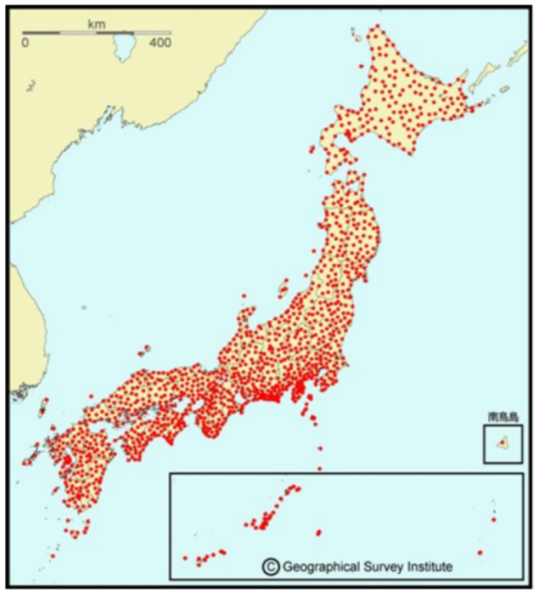

Fig. 11. GPS stations of the GEONET operated by GSI (source: http://terras.gsi.go.jp/gps/gps-based_control_station.html).

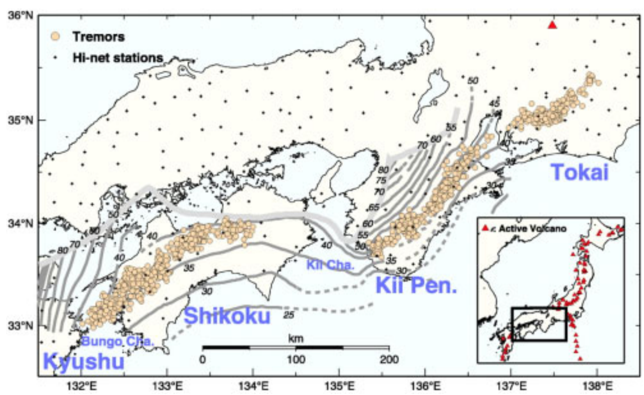

Fig. 12. Epicentral distribution of the deep low-frequency tremors in southwestern Japan in 2001 ([28]; reprinted with permission from AAAS).

the earth, such as slow slip on plate boundaries and non-volcanic deep low-frequency tremors (**Fig. 12**) [28]. To date, most of these networks have detected co-seismic, post-seismic, and inter-seismic signals. They may help clarify the physics of earthquake generation and the surrounding environment.

The 2003 M8.0 Tokachi-oki earthquake is a good example illustrating the value of observation networks and earthquake research. The site and size of this earthquake were consistent with the forecasts by the long-term evaluation. The location of asperities and distribution of seismic intensities are similar for the 2003 and 1952 Tokachi-oki earthquakes, and this similarity may provide the scenario for a future subduction-zone earthquake and its ground motions. The partitioning of coseismic slip and afterslip was clarified, and ocean bottom seismometers and 1 Hz sampling GPS became useful tools. The immediate release of these observation records also promotes

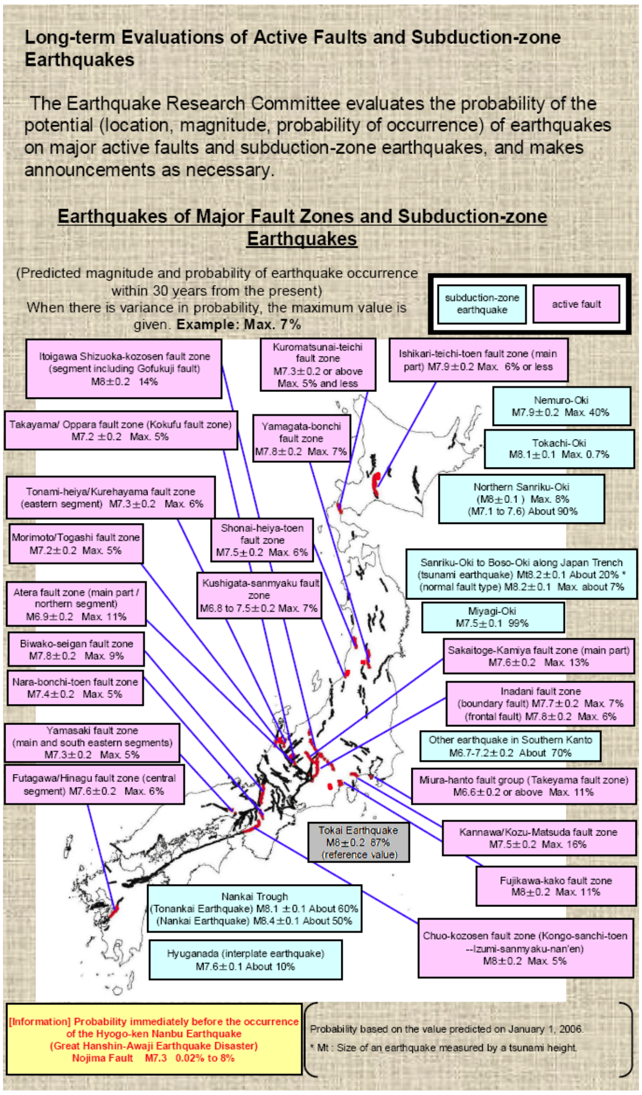

Fig. 13. Long-term evaluation of earthquake occurrence probabilities for active faults and subduction-zone earthquakes by HERP (source: http://www.jishin.go.jp/main/w_30_f-e.htm).

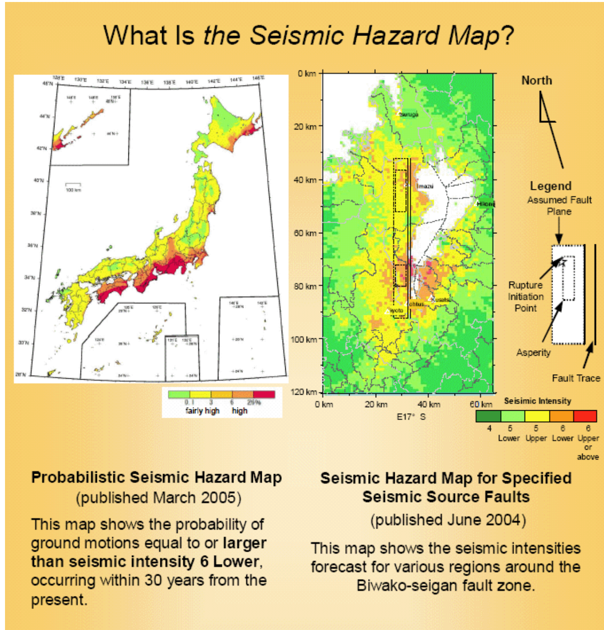

Fig. 14. Probabilistic (left) and scenario (right) seismic hazard maps by HERP (source: http://www.jishin.go.jp/main/w_30_f-e.htm).

realtime or semi-realtime seismology for hypocenter relocation and source inversion.

5. Strong Motion Seismology After 1995

As mentioned earlier, the 1995 Kobe earthquake produced devastating damage and loss of life in Kobe, on the Awaji island, and in surrounding regions. The earthquake was caused by active faults beneath these areas. The most heavily damaged area in Kobe, called a damage belt, is located 1 km southeast away from the assumed fault trace, which nearly coincides with the basin edge (border between the mountainous and sedimentary areas). Due to this finite offset, strong arguments arose about the location of the faults that cause destructive ground motions. The slip distribution recovered by waveform inversion of strong motion data shows concentrated slips in a shallow part of the Awaji island and a deep part beneath Kobe. This deep concentrated slips produced forward rupture directivity effects on Kobe. Ground motion simulation using a 3-D velocity structure model of the Kobe area succeeded in reproducing the damage belt with an offset from the assumed fault trace. In short, the destructive ground motions during the 1995 Kobe earthquake were caused by both the forward rupture directivity and basin edge effects [29].

In relation to strong motion seismology, the 1995 Kobe earthquake points up the importance of comprehensive research involving source, path, and site studies. High-quality data from the nationwide dense observation networks mentioned earlier support this sort of study, promoting earthquake source studies using kinematic and dynamic approaches, large-scale high-performance ground motion simulation, modeling of velocity structure, and ESG (Effects of Surface Geology) studies after the 1995 Kobe earthquake.

In addition to affecting the NIED's K-NET and KiK-net, the 1995 Kobe earthquake also changed the JMA's strong motion observation. Preceding the earthquake, seismic intensities were reported by JMA officials at local stations based on their impressions of experienced shaking and observations by sight. However, this system was of little use in areas heavily damaged by the earthquake, so the JMA completely changed the system to instrumental measurements in 1996. About 4,000 seismic intensity meters, which are actually strong motion seismographs with automatic intensity calculation facility, were deployed by the JMA and local governments across the Japan islands. This extremely dense network enabled researchers to visualize the propagation of long-period ground motion even within a single basin [30]. Damaging long-period ground motion and its long-range effects, for example, were observed by these dense arrays during the 2003 Tokachi-oki earthquake.

In a major objective of earthquake research promotion in March 2005, the Headquarters for Earthquake Research Promotion released the “National Seismic Hazard Maps for Japan [31],” consisting of probabilistic and scenario seismic hazard maps. The probabilistic seismic hazard map shows the probability of seismic shaking in a specific region within a certain period based on long-term evaluation of earthquake occurrence probabilities for active faults and subduction-zone earthquakes (**Fig. 13**) and empirical attenuation relationship for ground motions as a function of distance from a fault. The scenario seismic hazard map provides a distribution of shaking and broadband ground-motion time histories based on a recipe for predicting strong ground motions from specific earthquake faults with a high potential for occurrence (**Fig. 14**). The recipe describes a procedure how to model a future earthquake source using the characterized source model consisting of asperities and a background area [32]. Ground motions from the asperities characterize the amplitudes and periods of directivity pulses causing damage such as that by the 1995 Kobe earthquake. The feasibility of these probabilistic and scenario seismic hazard maps was verified in the 2003 Tokachi-oki earthquake, for which they showed good agreement with spatial patterns of observed seismic intensities. Waveforms simulated by the recipe agreed well with seismograms observed by the dense strong-motion networks.

These maps are the results of cooperative research by the subcommittees for long-term evaluations and evaluation of strong ground motion at the Earthquake Research Committee of the Headquarters for Earthquake Research Promotion. The hazard maps themselves and their methodology are being widely used. In addition to these nationwide seismic hazard maps, the Central Disaster Prevention Council and local governments have started publishing regional seismic hazard maps for megathrust earthquakes around the Japan islands and fine-mesh maps for individual cities, respectively [33].

6. Summary and Prospects

Earthquake observation and strong motion seismology in Japan changed dramatically after the 1995 Kobe earthquake. Since then, the nationwide observation networks have been strengthened under the direction of the Headquarters for Earthquake Research Promotion, and have succeeded in detecting co-seismic, post-seismic, and inter-seismic signals that are expected to lead to a better understanding of earthquake generation mechanisms. The quality of source inversion and the development of ground motion simulation enable us to predict realistic strong ground motions. The National Seismic Hazard Maps released in 2005 as a result of comprehensive research on long-term evaluation of earthquake occurrence and strong ground motion prediction are expected to prove useful in earthquake disaster mitigation and scientific outreach to the public.

We are facing future earthquakes whose probabilities of occurrence are estimated to be high in long-term evaluation. Even though modeling and simulation of earthquake generation mechanisms and precise earthquake prediction are progressing, the nationwide observation networks and hazard maps are ready, and the next disastrous earthquake may prove to be the touchstone of earthquake observation and strong motion seismology in Japan.

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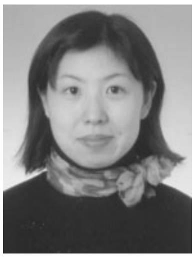

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