Trends and Problems in Earthquake Prediction Research

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1 Introduction

The M8.0 earthquake (M: magnitude) which struck Sichuan Province in China on May 12, 2008 was a major disaster of historic proportions, resulting in a total of nearly 100,000 dead and missing. According to newspaper reports, dissatisfaction over the fact that no information predicting this earthquake was provided erupted in the affected area. In particular, the large number of victims claimed by the collapse of elementary and middle school buildings is viewed as a problem, and there has also been criticism to the fact that China's earthquake countermeasures have devoted energy to observation of well water and the earth's crust, but seismic countermeasures for buildings have been delayed.[1] This tragedy may become the occasion for a review of policies in connection with earthquake disaster prevention in China and will perhaps lead to seismic retrofitting of buildings. Even though the shock of the Sichuan earthquake had still not subsided, Japan was struck by the Iwate-Miyagi Nairiku Earthquake (M7.2) on June 14, which caused more than 20 deaths. This was followed by the Iwate-Chubu Earthquake (6.8) on July 24. All of these events have strengthened the impression that earthquakes strike unexpectedly, at any time and place. Expressions of this sort have become a way of disposing of the matter and have taken root in the mass media. Considered from another direction, however, it can also be said that this is a clear manifestation of distrust toward earthquake prediction research as it now exists. What, then, is the current state of earthquake prediction research?

Although prediction had been considered a central challenge for earthquake research, not limited to China, but worldwide, this trend changed around the mid-1990s. In Japan, this was occasioned by the Great Hanshin-Awaji Earthquake (M7.3), which struck Kobe on January 17 causing more than 6,400 deaths, 1995, and subsequently led to a review of earthquake countermeasures as a matter of national policy. Accompanying this, a complete change in earthquake research was unavoidable, and the previous single-minded dedication to earthquake prediction was replaced by specialization either in more practical disaster prevention research or in more fundamental scientific research. However, this does not mean that earthquake prediction as such was neglected. The proper course in science is "prediction of future events based on an analysis of past events." It should perhaps be said that this attitude was an attempt to take a more scientific stance toward the word and concept of "prediction," which had been used easily or somewhat carelessly up to that time. Today, more than 10 years since that change in direction, what is the relationship of the reformed earthquake research to prediction, and what contribution has it made? Have we not reached the time when we should stop and look back on how close we have come to achieving the specified target, and whether we have failed to grasp the target itself?

This paper examines the content of related research, divided into "earthquake prediction" in the narrow sense and "earthquake forecasting." Although there are no large differences in the meanings of the words "prediction" and "forecasting" themselves, here, they will be distinguished as follows: "Earthquake forecasting" means estimation of the magnitude and probability of the occurrence of an earthquake which may occur in a certain location, when that location is designated. The probability of occurrence is obtained by statistical operations premised on the fact that earthquakes occur repeatedly in the same location, and is based on information obtained by excavation of past evidence, that is, the scale, cycle, and deviations in the cycle of earthquakes, and the time which has elapsed since the most recent earthquake. In this case, the information which provides the grounds for the probability value does not change with increasing time in spite of the fact that the probability value increases with time. In contrast, in "earthquake prediction," how close the accumulated stress in the source area is to the limit is estimated from the transition in measured data, when a designated earthquake is the object. In other words, premised on detection of some type of precursory phenomenon, this approach attempts to increase the amount of information itself prior to the occurrence of an earthquake, and in particular, to dramatically increase information immediately before the earthquake. While reviewing the history and current status of both "earthquake forecasting" and "earthquake prediction," the author would like to analyze the problems involved in both approaches, including his personal impressions.

2 Evolution of earthquake prediction research

2-1 Frequency of destructive earthquakes in Japan

First, let us confirm the frequency with which earthquakes actually occur in Japan. This is simpler if earthquakes are classified by magnitude. The average annual frequency of earthquakes in Japan and the surrounding oceans is 0.1 for M8 earthquakes, 1 for M7, and 10 for M6. Thus, frequency increases by approximately 1 order (10 times) for each 1 order decrease in magnitude. The frequency of earthquakes worldwide is approximately 10 times these numbers, which means, conversely, that approximately 10% of the world's earthquakes occur in Japan and the oceans that surround it.[2] For this reason, Japan is known as an earthquake-prone country. What essentially concerns ordinary people is not the size of an earthquake itself, but the extent of damage that it causes. However, the frequency of earthquakes which caused considerable damage in the past is larger than most people recognize.

Table 1 presents a list of earthquakes since 1900 which caused 10 or more deaths. Figure 1 is a graph showing the secular change in their cumulative frequency. There have been a total of 36 of these destructive earthquakes during the past 109 years, and their average interval is 3.1 years. From the graph, it appears that the frequency of destructive earthquakes has decreased since 1950, but this seems to be due to slightly decreased seismic activities during the last 50 years, rather than the effects of promoting seismic countermeasures. However, even while saying that the frequency of earthquakes is low, the average interval in the latter part of the period is 4.5 years, and a revival of activity can also be seen in recent years.

Table 1 : List of earthquakes causing 10 or more deaths/missing persons in Japan since 1900
(Year, location, magnitude, number of dead/missing)

Major destructive earthquakes (10 or more dead/missing)

1900 Miyagi Hokubu (M7.0)	17
1901 Hachinohe-oki (M7.2)	18
1905 Geiyo (M7.3)	11
1909 Anegawa (Eno) (M6.8)	41
1911 Kikaijima (M8.0)	12
1914 Akita Semboku ((M7.1)	94
1914 Sakurajima (M7.1)	35
1922 Chijiwa Bay (M6.9)	26
1923 Kanto (M7.9)	142,807
1924 Tanzawa (M7.3)	19
1925 Kitatajima (M6.8)	428
1927 Kitatango (M7.3)	2,925
1930 Kita Izu (M7.3)	272
1931 Nishi Saitama (M6.9)	16
1933 Sanriku (M8.1)	3,064
1939 Oga (M6.8)	27
1940 Kamui Misaki-oki (M7.5)	10
1943 Tottori (M7.2)	1,083
1944 Tonankai (M7.9)	1,223
1945 Mikawa (M6.8)	2,306
1946 Nankai (M8.0)	1,330
1948 Fukui (M7.1)	3,769
1949 Imaichi (M6.4)	10
1952 Tokachi-oki (M8.2)	28
1964 Niigata (M7.5)	26
1968 Tokachi-oki (M7.9)	52
1974 Izu Hanto-oki (M6.9)	30
1978 Izu-Oshima-kinkai (M7.0)	25
1978 Miyagi-oki (M7.4)	28
1983 Nihon-kai Chubu (M7.7)	104
1984 Nagano Seibu (M6.8)	29
1993 Hokkaido Nansei-oki (M7.8)	202
1995 Hyogo Nanbu (M7.3)	6,437
2004 Chuestsu (M6.8)	68
2007 Chuetsu-oki (M6.8)	15
2008 Iwate-Miyagi Nairiku (M7.2)	23

Prepared by the STFC based on Reference [3]

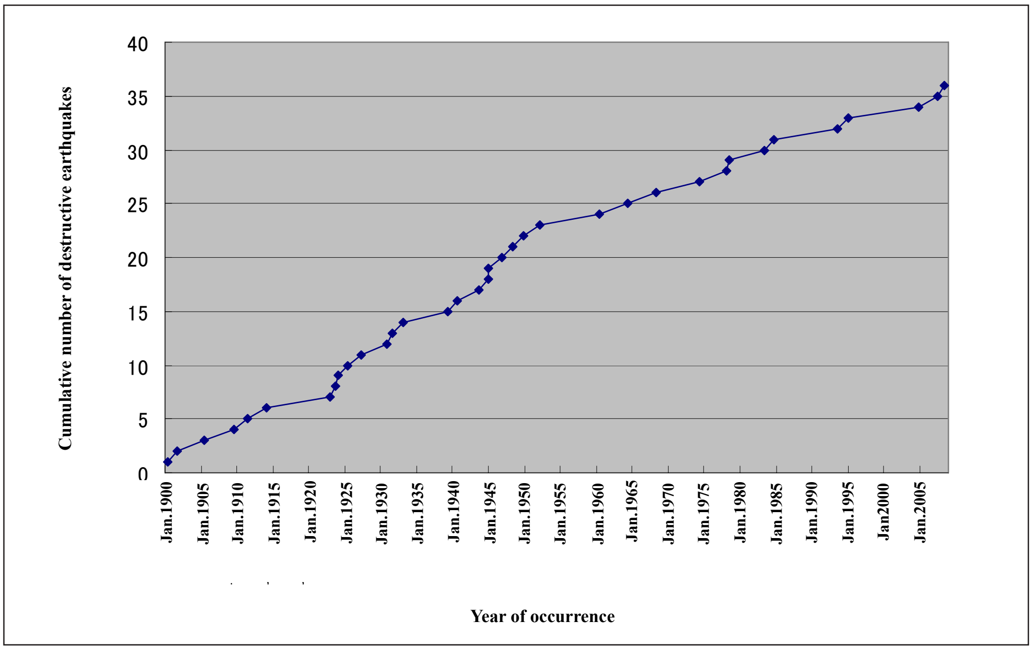


Figure 1 : Distribution of cumulative number of destructive earthquakes (data at points in Table1)

Prepared by the STFC

The feeling that earthquakes occur at long intervals and have no particular relationship with oneself, in spite of the actual situation, can be attributed to the fact that people do not know where a given earthquake will strike. The objective of researching earthquakes should be to give some type of answer to this question, namely, where and what kind of earthquakes will occur in the future. In this sense, earthquake prediction, while being a challenge for scientific research, was at the same time a “dream” of humankind. However, prediction is still a “dream” today. This is because there are still no examples which are widely recognized as successful earthquake prediction in the strict sense. Therefore, let us begin by tracing the history of earthquake prediction research up to the present.

2-2 History of earthquake prediction research in various countries

Saying that there have been absolutely no successful attempts in earthquake prediction may be somewhat misleading. First, some examples which are generally considered to be successful predictions should be mentioned. The most famous example is the Haicheng earthquake (M7.3) in Heibei Province, China in 1975.[4] Seismic activity had become active in the vicinity several years before the earthquake, and various anomalous phenomena, including microtremors, crustal movements, and changes in the groundwater, occurred frequently beginning several days before the event. The earthquake warning which was issued based on these precursory phenomena was effective, and a large number of people were able to take refuge. In spite of this, it is difficult to recognize this success as the result of earthquake prediction in the scientific sense because no warning was issued before the Tangshan Earthquake (M7.8) which struck the same Hebei Province in 1976 and caused an historically-unprecedented 240,000 deaths. Although it seems that China subsequently continued with attempts at earthquake prediction, there have been no reports of success. The 2008 Great Sichuan Earthquake mentioned in the Introduction is an example of failure. Thus, in view of the inability to demonstrate reproducibility and universality, the above-mentioned example cannot be regarded as a scientific achievement.

Another well-known example of research is the VAN method in Greece. Greece is extremely seismically active because it is located at a plate convergence zone, and as a result, it has suffered much damage due to earthquakes exceeding M5. A research group led by Prof. Varotsos of the University of Athens proposed a method of earthquake prediction based on anomalous changes in monitoring signals from a seismic geoelectric potential observation network installed at the southern edge of the Balkan peninsula. A successful example which resulted in an actual evacuation in 1993 was reported.[5] However, some have also expressed doubts about the objectivity of this method because the mechanism responsible for producing the anomalous subterranean electrical signals as a precursory phenomenon is unknown. On the other hand, another report supported the reliability of the VAN method based on a statistical study.[6] Although no conclusion has been reached, the VAN method has had a large effect on this area of research, and in Japan as well, earthquake prediction by electromagnetic techniques now occupy the mainstream position in sessions on earthquake prediction at conferences, taking precedence over mechanical methods based on seismic and crustal movements, groundwater, and the like.

The fact that the VAN method has become the main topic in conferences stirred a worldwide debate as to whether earthquake prediction is possible in principle. This debate was ignited by Prof. R.J. Geller (then Assistant Professor), who had recently joined the University of Tokyo from Stanford University. Prof. Geller contributed papers to Nature and other journals asserting that prediction is impossible in principle because the time of occurrence and magnitude of earthquakes is controlled by contingency.[7] This claim was countered by a group led by Prof. M. Wyss of the University of Alaska (now at WAPMERR (World Agency of Planetary Monitoring and Earthquake Risk Reduction), who held an international symposium on earthquake prediction and argued that precursory phenomena unmistakably exist. Thus, in the 1990s, an unprecedented controversy developed between a faction claiming that earthquake prediction was possible and a faction claiming it was impossible. Thereafter, the controversy was gradually forgotten without reaching any definitive conclusion, and earthquake prediction research as a whole showed a declining tendency.

The United States was no exception to this trend. Interest in earthquake prediction research in the United States is concentrated on the San Andreas Fault on the West Coast. This can be attributed to the fact that the Fort Tejon Earthquake (M8.0) which struck Los Angeles in 1857 and the 1906 San Francisco Earthquake (M7.8) occurred along this fault, and a recurrence of these earthquakes is feared. Because this fault undergoes steady slip motion in the intermediate area between these two great earthquakes, great earthquakes do not occur in the intermediate region. M6 class earthquakes had occurred at intervals of somewhat more than 20 years near the town of Parkfield, which is located in this region, and the next earthquake was forecast to occur by 1993. As there was no concern about injury due to an earthquake of this size in that area, this was perceived to be a favorable opportunity for earthquake prediction. Numerous observation devices and human monitors were concentrated at the site for an earthquake prediction experiment call the “Parkfield Experiment,” but the expected earthquake failed to materialize. An M6 earthquake actually occurred in 2004, which was more than 10 years late and was probabilistically low, but in this case, the expected precursory phenomena were not detected.[8] This marked a turning point, after which earthquake prediction research also waned in the United States, following the trends in other countries.

2-3 History of earthquake prediction research in Japan

Japan has always played a leading role in earthquake prediction research. In 1962, the authorities in the scientific world of the time compiled recommendations on the direction of earthquake prediction research in a document called “Earthquake Prediction-Current Status and Plans for Its Promotion” (so-called “Blueprint”), and based on this, an earthquake prediction project was launched in 1965 with a budget from the government.[9] The Coordinating Committee for Earthquake Prediction (hereinafter, Coordinating Committee) was established in 1969, and as an advisory body to the President of the Geographical Survey Institute, its activities have continued to the present. In 1970, the Coordinating Committee identified seismic hazard regions nationwide and issued recommendations that observation and monitoring should be strengthened in these areas (subsequently revised in 1978). In designating these areas, areas were selected not based only natural conditions, but also considering social conditions. According to Yoshimitsu Okada (now President of the National Research Institute for Earth Science and Disaster Prevention), many major earthquakes have occurred in the designated area in the 29 years since the revision, including the Great Hanshin-Awaji Earthquake, and a prediction success rate of 80% was achieved. (Figure 2).[10] On the other hand, Katsuhiko Ishibashi, who was an assistant in the Earthquake Research Institute at the University of Tokyo at the time (and later became a Professor of Kobe University), presented his theory of a

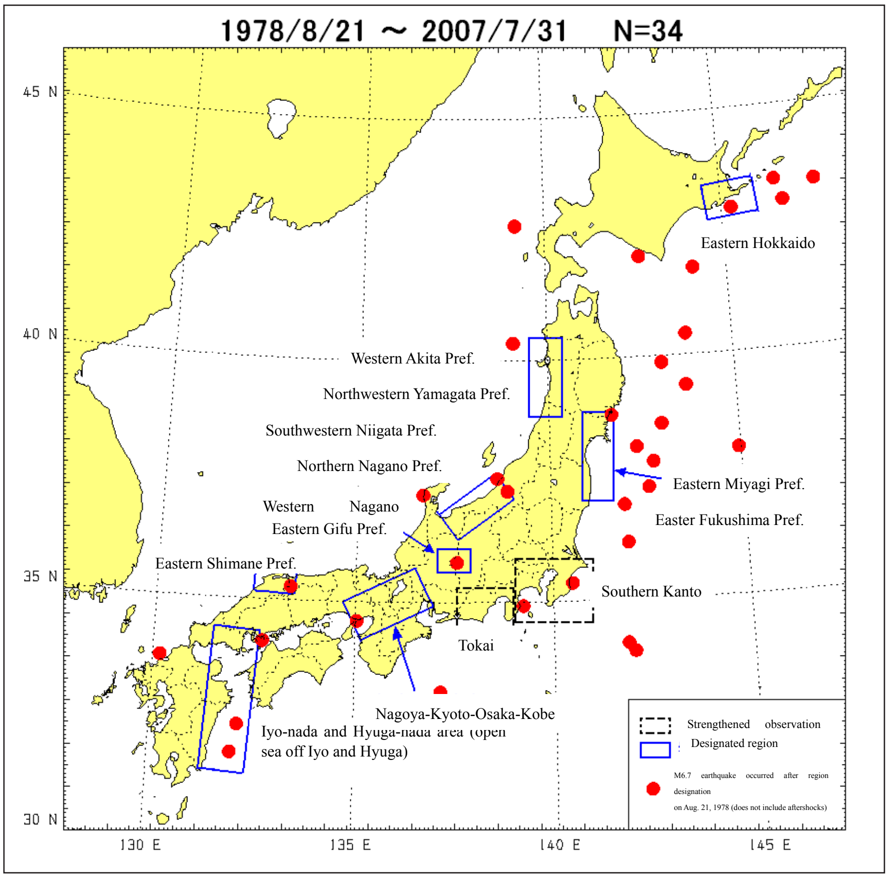


Figure 2 : Regions designated by the coordinating committee for earthquake prediction and actual earthquakes M6.7 or larger

Source : Reference [12]

Great Suruga Bay Earthquake at the 1976 Autumn Conference of the Seismological Society of Japan.[11] At Suruga Bay, strain has continued to accumulate for more than 120 years since the Ansei-Tokai Earthquake of 1854, and it has been pointed out that this area is now at an extremely volatile crisis point. The government attached considerable importance to Ishibashi's theory, and in 1978, enacted the first law, which was called the "Special Measures Law for Countermeasures against Large Earthquake,"[12] for earthquake countermeasures for a M8 class Suruga Bay Earthquake, i.e., a Tokai Earthquake. Based on this law, the area where a seismic intensity of 6 or higher was assumed, centering on Shizuoka Prefecture, was demarcated as an "Area under Intensified Measures against Earthquake Disaster," and routine monitoring of this area was assigned to the Japan Meteorological Agency. In order to fulfill its mission of predicting Tokai earthquakes, the Japan Meteorological Agency organized the "Earthquake Assessment Committee for Areas under Intensified Measures against Earthquake Disaster (EAC)," which thereafter held monthly meetings to discuss arrangements. During this period, in 1978, the Izu-Oshima-Kinkai Earthquake (M7.0) occurred on the active fault between the Izu Peninsula and Izu-Oshima Island, causing 25 deaths. In this earthquake, anomalous phenomena were discovered before the actual occurrence in a diverse range of observation items, including seismic activity, crustal movement, groundwater level, radon gas concentration, and others. Thus, it was evaluated that there still remains one step away to actually predicting earthquake.[13] In 1977, a group headed by Masakazu Otake (now Professor Emeritus of Tohoku University and Chair of the above-mentioned Coordinating Committee) discovered a quiescence in seismic activity around Oaxaca in Mexico and published a paper warning of an impending major earthquake. The following year, in 1978, the M7.7 Oaxaca Earthquake occurred, giving a strong impression that earthquake prediction is possible.[14] From the 1970s through the 1980s, Japan developed a nationwide microtremor observation network, and earthquake prediction research centers were established in universities and national research institutes. In view of these and similar examples, it can be said that this was the period when earthquake prediction aroused the highest expectations in Japan, and it was believed that earthquake prediction would be realized in the near future.

2-4 Impact of the Great Hanshin-Awaji Earthquake

On January 17, 1995, when the worldwide debate on the possibility of earthquake prediction was at its peak, the Great Hanshin-Awaji Earthquake (M7.3) occurred unexpectedly, rupturing an active fault from the city of Kobe to Awaji Island, and more than 6,400 persons died in the ensuing disaster. Although some reports had forecast this earthquake, the residents of the region gave hardly any thought to the danger of a massive earthquake. Therefore, there was strong criticism of earthquake research, which had not issued effective advance warnings in spite of the unprecedented numbers of victims in recent years. This became the occasion for a sweeping review of the position of prediction research. The impact of the Hanshin-Awaji Earthquake was also sufficient to cause a major change in national policy. While this did not led to a rejection of the concept of earthquake prediction, dependence on prediction in earthquake countermeasures was fundamentally eliminated. Concretely, a new Earthquake Research Division was established in the former Science and Technology Agency (later moved to the Earthquake and Disaster-Reduction Division, MEXT). The "Headquarters for Earthquake Prediction Research Promotion" which had existed up to that time was renamed the "Headquarters for Earthquake Research Promotion" (hereinafter, "HERP"), and was also reorganized.[15] A Policy Committee and an Earthquake Research Committee were established under HERP, and a large number of sectional meetings and subcommittees were established. These committees conduct short-term and long-term assessments of Japan's earthquake activities and communicate the results to the larger society by way of the mass media. The name "prediction" in administrative organizations was removed or changed. However, this does not mean that "prediction" was eliminated completely. At one time there was a view that overlapping of the Earthquake Prediction Coordinating Committee and the Earthquake Research Committee was a problem and the Coordinating Committee should be abolished, but ultimately the Coordinating Committee has continued to exist up to the present. In spite of the fact that discussions in the two Committees partially overlap, their purposes and the nature of their evaluations are slightly different. The Earthquake Assessment Committee in the Japan Meteorological Agency also survived. Although this is due to the formal provisions of the existing law, this body has continued to exist because hopes for prediction have not been abandoned, at least in the limited case of Tokai earthquakes. In this connection, it may be noted that the Central Disaster Management Council conducted a review of the assumed source area of Tokai earthquakes in 2001.[16] Based on new observational information, the source area that had existed until that time was greatly revised, and the object area for disaster prevention countermeasures was expanded. However, the basic framework and approach to prediction remained unchanged.

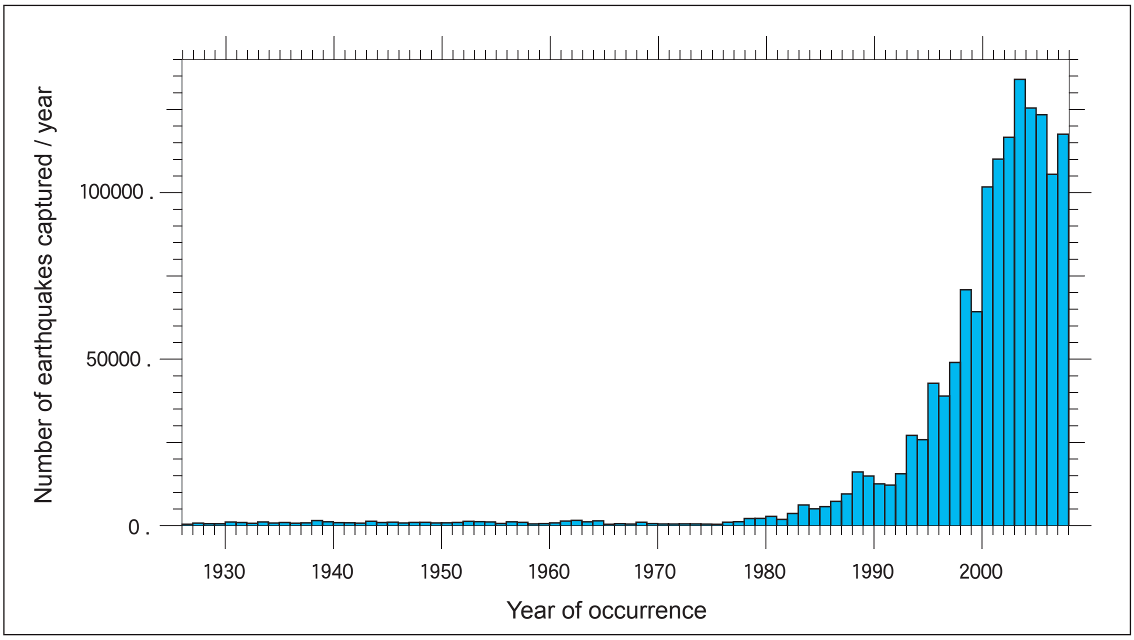
3 Change to earthquake forecasting

As a change in policy accompanying the establishment of HERP, administrative policies changed from the former orientation toward prediction to forecasting the occurrence of earthquakes. As mentioned previously, earthquake forecasting does not pursue precursory phenomena, but rather, assesses the probability of the occurrence of a major earthquake statistically, based on an assessment of active faults and events which have occurred in the past.

3-1 Construction of the Kiban Network (basic nationwide seismic network)

One aspect which underwent a major transformation was the nationwide observation network.[15] The basis of observation of crustal movement is observation of earthquakes and crustal movement (expansion/contraction, rising/falling of the ground surface). Up to that time, however, observation of earthquakes had been the responsibility of the Japan Meteorological Agency, universities, and national research institutes, while the Geographical Survey Institute had been responsible for observation of crustal movement. It can be said that this period was an "age of rival warlords." While these various organizations provided coverage for the entire country, the observational density was coarse. Moreover, specifications were not unified. More than anything else, this was a high barrier to mutual use of data between organizations. An enormous length of time, on the order of several years, and a corresponding amount of work were required in making geodetic measurements of the entire country. With the world in the midst of the IT revolution and rapid technical progress in the fields of observation, communications, and data processing, an outdated observation network which failed to change was fated to be left behind. Therefore, following the Great Hanshin-Awaji Earthquake of 1995, HERP decided to budget new funds and promote the construction of a nationwide observation network based on unified specifications. Broadband, high accuracy technology was adopted for seismic observation, and quasi-real time measurement using GPS was applied to crustal movement. As a result, in less than 10 years, Japan succeeded in constructing a high performance, high density observation network unprecedented in the world. The content of what came to be called the "Kiban Network" (basic nationwide seismic network) comprises a crustal movement observation network using GPS (approximately 1400 points nationwide, centering on GEONET by the Geographical Survey Institute), a high sensitivity seismograph observation network (approximately 1000 points, centering on Hi-net of the National Research Institute for Earth Science and Disaster Prevention (NIED)), a strong ground motion observation network (approximately 7000 points including the NIED's K-net), and a broadband seismograph observation network (approximately 100 points, centering on NEID's F-net). It is particularly noteworthy that all the data obtained by this Kiban Network are publicly available via the internet. As a result, researchers throughout the country are placed in virtually the same research environment concerning the availability of data, irrespective of the university or institute to which they belong, and this at a stroke has accelerated free competition in research. Now, when a destructive earthquake or other earthquake which should be considered a problem occurs, the basic information characterizing the earthquake, such as the geometry of the fault system, rupture process, etc., is analyzed and reported extremely quickly. Figure 3 shows the transition in the number of earthquakes captured in and around Japan from the earthquake catalog of JMA (the Japan Meteorological Agency). This does not mean that there was a particularly great change in seismic activity as such during this period, but the number of earthquakes captured has increased steadily as the observation network was expanded. In particular, it can be understood that the increase was very rapid from around 2000, when the Kiban Network came on-stream.

Furthermore, in recent years, the reach of research and observation has expanded from land to ocean areas. JAMSTEC (Japan Agency for Marine-Earth Science and Technology) constructed a deep sea drilling vessel called the "Chikyu" and has begun research on the deep crustal structure of the earth in ocean areas, and is also promoting the development



* The rapid increase from around the year 2000 was due to the implementation of the Kiban Network.

Figure 3 : Number of earthquakes captured in and around Japan by the Japan Meteorological Agency

Source : Reference [12]

of a sea-bottom seismograph network to cover Japan's coastal seas.[17] The Japan Coast Guard and universities are engaged in the development of a crustal movement observation network in ocean areas by combining GPS and acoustic ranging devices installed on the sea bottom.[18]

It can be said that the construction of a nationwide observation network, beginning with the Kiban Network, has had a great effect on the promotion of earthquake research as a whole, including the disaster prevention aspect, but this does not mean that there are no problems in these efforts. The following two points may be mentioned as misgivings of the author, mainly in connection with the operational aspect. In the "age of rival warlords" before the construction of the Kiban Network, the former Imperial universities had substantial jurisdiction over their respective regions, separately from the nationwide network administered by JMA. For example, Hokkaido University had jurisdiction in Hokkaido, Tohoku University in Tohoku, Tokyo University in Kanto and Shinetsu, Nagoya University in Chubu, Kyoto University in Kinki, Chugoku, and Shikoku, and Kyushu University in Kyushu. This method of dividing jurisdictions led to partitioning of the data, creating barriers to research activities, and became a starting point for reflection after the Great Hanshin-Awaji Earthquake. Conversely, however, this system also was a factor that produced a consciousness and sense of responsibility as a "home doctor," because each university was responsible for monitoring and evaluating the crustal movements in its own area. In contrast, the present system has produced a situation of excessive competition, with connotations of a certain kind of waste, in that researchers throughout the country are engaged in exactly the same analysis using identical data. This can perhaps be called progress, in the sense of speeding up processing and unifying information management. However, from the standpoint that one wishes to recommend monitoring and research from a long-term perspective by a "home doctor," who has a thorough knowledge of the tectonics (structural motion, represented by plate tectonics) and condition of activity of that researcher's own region, the feeling of a kind of dilemma is unavoidable.

Secondly, there are also differences in the time scale in the cycle of earthquake occurrence and in the speed of technical innovation. Considering the fact that one cycle of an earthquake is at least several decades to several centuries, continuation of observation over the long term under stable conditions is an essential condition. However, it is difficult to avoid changes in observation conditions due to technical innovation and the evolution of the system. This is also a dilemma. Technical innovation does not necessarily lead to good results. For example, the Earthquake Catalog (Figure 3) prepared by the Japan Meteorological Agency, which covers more than 80 years, is an invaluable data resource of which Japan can boast to the world, but due to technical innovations and changes in the system, the magnitude shown in the Catalog is not uniform. This has greatly reduced the value of the data so painstakingly collected. Long-term maintenance and operation of the Kiban Network, which is deployed on a large scale, is also accompanied by greater difficulties than construction and maintenance of the system. It is necessary to be aware that preserving the consistency of observations unaffected by changes in the larger environment is an important challenge for the future.

3-2 Preparation of Seismic Hazard Maps

HERP is engaged in the preparation of a "National Seismic Hazard Map of Japan" as a fundamental part of its mission.[15] As mentioned previously, "forecasting," as the term is used here, means an assessment of the probability of the occurrence of the next earthquake preconditioned on an assumption that earthquakes occur with quasi-regularity in a given location. Although the existence of precursory phenomena is still a matter of debate, the majority of researchers support the quasi-regularity of earthquakes. This is also a reason for the change in the policies of administrative authorities from "earthquake prediction" to "earthquake forecasting." The information necessary for an assessment comprises three parameters, namely, the earthquake occurrence period and its deviation and the date of the most recent earthquake for the earthquake in question. In addition, a statistical model which expresses the deviation from regularity is also necessary. HERP has adopted a BPT (Brownian Passage Time) model in which the rate of accumulation of a certain amount of stress is affected by random disturbances.

Based on these arrangements, the procedures which can actually be promoted are as follows. Although the earthquakes which occur in ocean areas, for example, along ocean trenches, have a scale on the order of

M8, their cycle is short, at several decades to several 100 years. Accordingly, evidence of many such earthquakes can be found in the historical record. As a result, assessment of the probability of occurrence is comparatively easy, and reliability is high. On the other hand, earthquakes which occur at shallow active faults in inland areas have long time scales of at minimum 1000 years or more, and their histories are virtually unknown. HERP specified 98 active faults with lengths exceeding 20km as major active faults (Figure 4; total of 110 as a result of subsequent additions), and conducted a survey of these faults. It then attempted to determine the values of the above-mentioned parameters for each of the active faults by performing trench excavation surveys (survey by excavating a shallow trench) and boring surveys (survey by boring a deep hole). In actuality, cases in which the values of parameters are determined conclusively are rare, and considerable deviations and indeterminacy cannot be avoided. Nevertheless, the provisional results were compiled over a period of 10 years. The numerical distributions of the magnitudes of the earthquakes which are assumed to occur here are as shown by the black bars in Figure 5, and their average magnitude is M7.3. (The total number is 136 because it is considered that earthquakes will occur in segments of the long and large faults among the 98 major active faults.) An assessment of active faults smaller than the major faults was also made, resulting in an average of M6.8 (shown by the white bars in Figure 5, total number of 178). In addition to these, as “earthquakes having a sources which are difficult to designate the seismic source,” the probability of occurrence of “problem earthquakes” was calculated from the actual measured distribution of the magnitude of the earthquakes and largest earthquake set in each region. The result of combining all of the above assessments is considered to be the earthquake occurrence probability at each location.

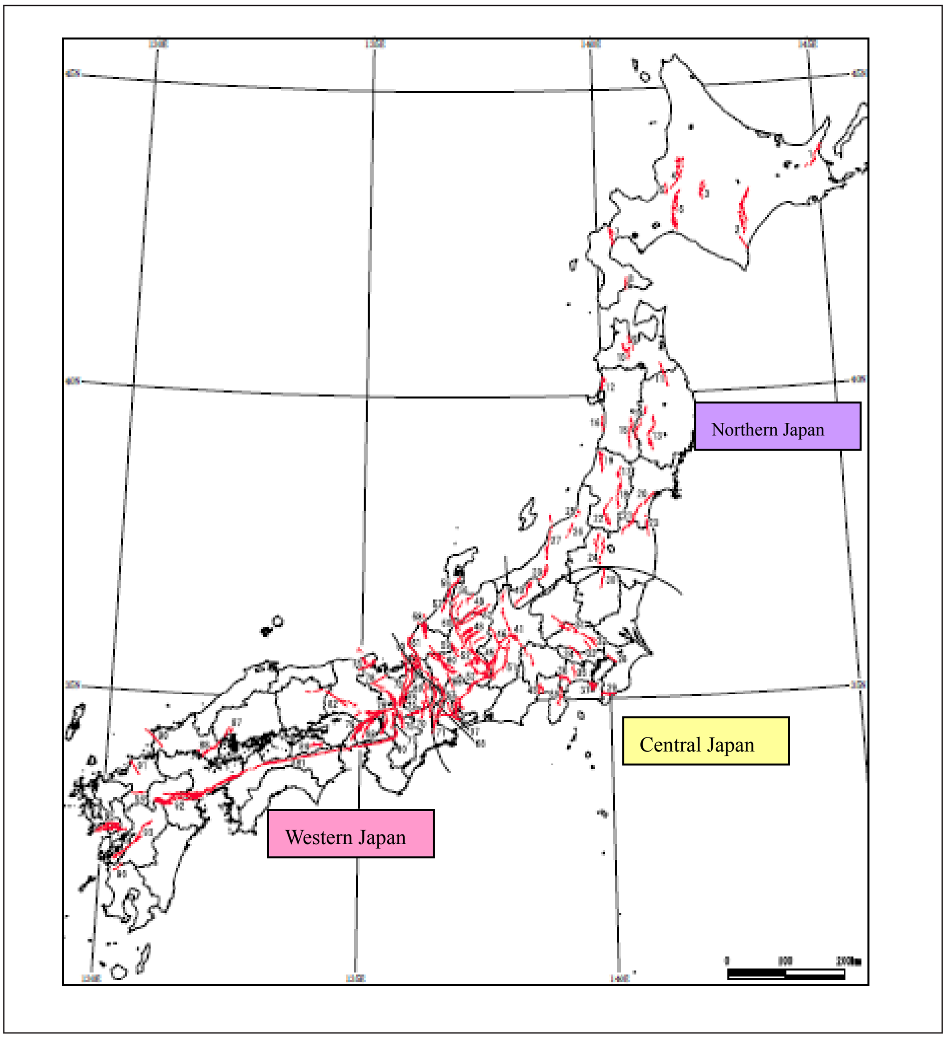


Figure 4 : Major active faults listed by the Headquarters for Earthquake Research Promotion

Source : Reference [15]

If the occurrence probability of earthquakes can be obtained, the procedure moves next to assessment of the motion at each location, that is, ground motion. Here, the final surface ground motion is calculated using a combination of various assessment techniques, including evaluation equations for motion based on the magnitude of the earthquake and the distance from the source, or a seismic wave synthesis method based on a fault model, and assessment of the amplitude of the seismic wave due to the subsurface structure and basement structure, etc. Local governments determine damage assumptions and disaster prevention countermeasures based on these results.

The detailed description of these procedures will be omitted here. However, the first trial edition of

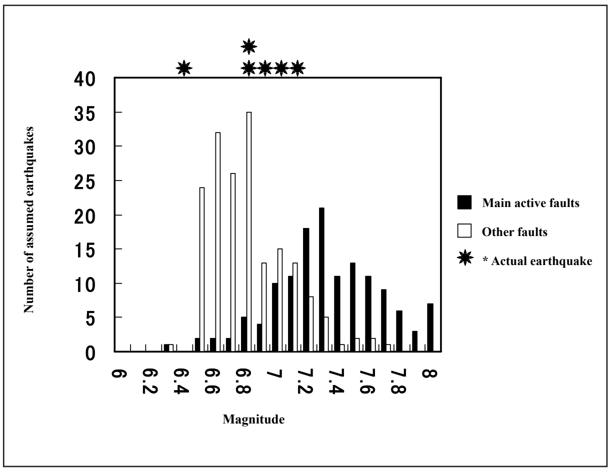
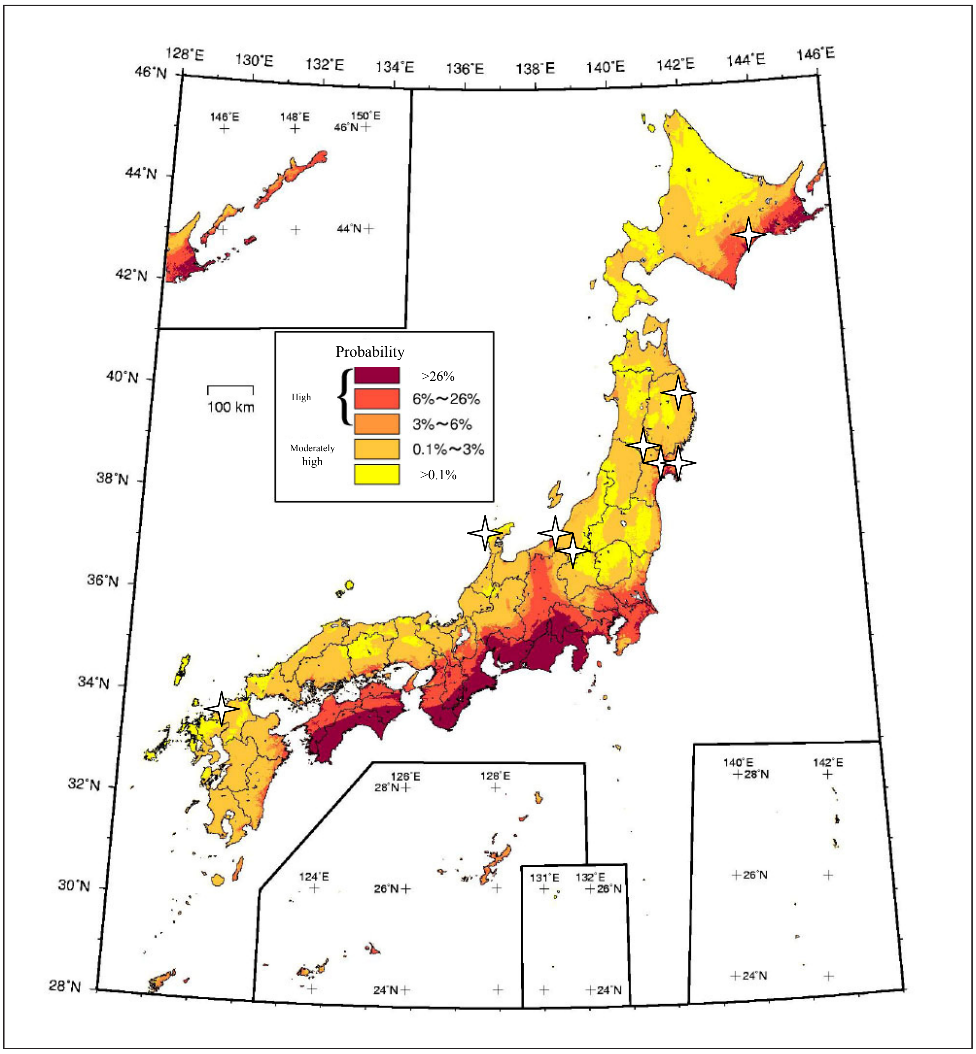


Figure 5 : Numerical distribution of magnitudes of assumed earthquakes occurring at inland active faults

Source : Reference [15]



Distribution of the probability of seismic motion of seismic intensity 6-Lower or higher within the next 30 years. White stars show the locations of actual 6-Lower and higher earthquakes in the most recent 5 year period. For the original map, see:
http://www.j-shis.bosai.go.jp

Figure 6 : Seismic Hazard Map

Source : Reference [15]

the "National Seismic Hazard Map" of Japan was published in May 2002, and the complete edition was published in March 2005, 10 years after the Great Hanshin-Awaji Earthquake (Figure 6).[19] Although the Hazard Map has been revised annually since that time, there have been no major changes. This map shows the probability of seismic intensity 6 Lower and higher earthquakes within the next 30 years in each region by color. The probability of occurrence of a 6 Lower earthquake, in other words, the risk of disaster, can be understood in 5 steps from the lowest probability of less than 0.1% to the highest probability of 26% or more. Almost all of the areas with the highest probability are distributed in a region lying along the Pacific Ocean from Shizuoka Prefecture to Kochi Prefecture. This is due to an impending ocean trench-type earthquake (Tokai-Tonankai-Nankai earthquake) along the Nankai Trough. In the region with the 2nd highest risk, with the exception of the Fossa Magna in central Japan, all lie along the Pacific coast. This is testimony to the fact that the frequency of inland active fault earthquakes differs by one order from that of ocean trench-type earthquakes.

3-3 Results of Seismic Hazard Map

As of 2008, only 3 years had passed since the publication of the complete edition of the Seismic Hazard Map. Accordingly, the accumulation of events is still inadequate for an evaluation. However, because problem earthquakes have also occurred during this period, it is necessary to evaluate the results by some method as a basis for future revisions. In other words, has "forecasting" really been successful?

Since the publication of the Seismic Hazard Map, including the trial edition, a total of 10 seismic intensity 6 Lower and higher earthquakes (shown by the white stars in Figure 6) actually occurred during the 5 year period up to October 8, 2008. Table 2 shows how the occurrence probability of these earthquakes was assessed in the Hazard Map using numerical values (30 year probability) which the author studied from a published report.[19]

First, because high occurrence probabilities of 60% for the Tokachi-oki Earthquake of September 2003 and 98% for the Miyagi-Oki Earthquake of August 2005 were shown in advance, it can be said that these interplate earthquakes occurred basically as forecast (for the Tokachi-Oki Earthquake, the value was immediately before occurrence of the earthquake; Miyagi-Oki is regarded as a fragment of the assumed earthquake). Among the remaining 8 earthquakes, the Miyagi-Oki Earthquake of May 2003 and the Iwate-Chubu Earthquake of July 2008 can be regarded as earthquakes within the Pacific Plate, and the Miyagi -Hokubu earthquake of July 2003 and the Niigata-Chuetsu Earthquake of October 2004 can be regarded as earthquakes at active faults other than the main active faults. The remaining four earthquakes were "unexpected" active fault earthquakes which occurred at an active fault in a coastal region or at an inland concealed fault (blind thrust fault). However, while these were also categorized as "earthquakes having sources that are difficult to designate the seismic source," this does not mean that there was no awareness of the occurrence of the earthquake as such.

Table 2 : Earthquakes of seismic intensity 6-Lower and higher in most recent 5 year period

			Assumed M	Probability of occurrence (%/30 years)	
May, 2003	Miyagi-oki Earthquake	M7.1	―	0.2～0.5	(intraplate earthquake)
Jul, 2003	Miyagi Hokubu Earthquake	M6.4	M7.1	0082	(Asahiyama flexure belt)
Sep, 2003	Tokachi-oki Earthquake	M8.0	M8.1	60	(interplate earthquake)
Oct, 2004	Chuetsu Earthquake	M6.8	M7.1	0.79	(Muikamachi fault zone)
Mar, 2005	Fukuoka Hokusei-oki Earthquake	M7.0	―	0.05	(coastal active fault)
Aug, 2005	Miyagi-oki Earthquake	M7.2	Mw7.4	98	(interplate earthquake)
Mar, 2007	Noto Hanto-oki Earthquake	M6.9	―	0.02～0.05	(coastal active fault)
July, 2007	Chuetsu-oki Earthquake	M6.8	―	0.2	(coastal active fault)
Jun, 2008	Iwate-Miyagi Nairiku Earthquake	M7.2	―	0.1～0.2	(geological fault)
Jul, 2008	Iwate Chubu Earthquake	M6.8	―	0.1～0.2	(intraplate fault)

Prepared by the STFC based on Reference [3]

The first two earthquakes mentioned above were ocean-trench type interplate earthquakes, and their occurrence probabilities were high. On the other hand, even assuming that the remaining 8 were supposed to be possible, their probabilities were considered to be extremely low. As a result, in a certain sense, it may be natural that the forecasts of the former were "hits" and the latter were "misses." Nevertheless, there are perhaps problems in this kind of simplistic summary.

Essentially, in order to assess "hits" and "misses" correctly, a complex statistical analysis is necessary. Here, however, only a simple trial calculation was performed. From Table 2 the average of the 30 year probability of the 8 earthquakes is 0.226%. Assuming the extent of the source of an average magnitude M7.0 earthquake is 200km2, the entire country of Japan would be divided into 1850 zones. If the probability of earthquakes occurring in 8 or more zones in a 5 year period is calculated for this case, the value is extremely small, at 0.0001%. In other words, in effect, the occurrence of these 8 earthquakes should be virtually impossible based on the assumptions. This indicates that there was some kind of problem in the assumptions.

3-4 Problems in seismic hazard map

In the preparation of the Seismic Hazard Map, "earthquakes at smaller active faults" and "earthquakes having sources (active faults) which are difficult to designate" were also considered. However, as discussed in the previous section, the results give an undeniable impression that earthquakes of around M7 occurred unexpectedly. Beginning immediately after the Noto Hanto-Oki Earthquake of March 2007, a number of newspapers published editorials to the effect that, "In Japan, it is impossible to escape earthquakes no matter where you live. The fact that the Seismic Hazard Map shows a low hazard level does not mean you can feel secure." Considering the level of the existing forecasting technology, the evaluation of the Seismic Hazard Map is extremely severe. It would also be hasty to evaluate the Seismic Hazard Map, which is essentially intended to be long-term information, based on the results from only 5 years. On the other hand, the Seismic Hazard Map is not a research paper, but rather, is information which the administrative authorities and researchers have presented to society. For this reason, how this information is received by society must not be ignored. At minimum, it is necessary to listen to criticisms that the forecasting of earthquakes at inland active faults was unsuccessful. Therefore, let us analyze the location of the problems in the current stage.

The first problem is that the active faults which cause earthquakes were not fully adequately captured. In Figure 5, the star marks indicate the magnitudes of six active fault earthquakes which actually occurred, overlaid on an assumed magnitude distribution map which was used in the Seismic Hazard Map. Comparing the form of distribution, it can be understood that these six earthquakes did not occur at the major active faults, but correspond to earthquakes occurring at smaller active faults other than the main faults. Among these, it seems possible to say that two earthquakes were assumed in advance, these being the July 2003 Miyagi-Hokubu Earthquake (Asahiyama flexure belt) and the October 2004 Chuetsu Earthquake (Muikamachi fault zone), but the remaining four were clearly missed. In Figure 5, the average magnitude of the earthquakes occurring from the major active faults was M7.3, while that of the earthquakes at active faults other than the major faults was M6.8, or a difference of 0.5 by magnitude. From this, it can be estimated that the earthquake occurrence frequency of the latter is $\sqrt{10}$ times that of the former. Furthermore, from the fact that the average interval between the occurrence of the former is 4200 years (harmonic average value), and that of the latter is 5300 years, if the number of active faults which are sources of these earthquakes is calculated, the number of active faults other than the major faults should be approximately 4 times that of the major faults (in this case, 136 major active faults), in other words, more than 500. In actuality, the number listed (178) is only about 1/3 of this number. Accordingly, it can be inferred that the majority of smaller active faults were not captured.

From the list of active faults in Chart 8, of the four earthquakes which were missed, it is considered that three were due to active faults in coastal areas, and one was due to a concealed fault which was not identified from the surface geological survey. Based on this result, On July 13, 2008, HERP announced a policy of identifying a total of 2000 active faults nationwide over the next 10 years, focusing on active faults in coastal areas and identification of concealed faults that seem to exist along the extensions of the main active faults.[21] However, it is estimated that many of the object active faults are less than 10km in length, and it is highly possible that small-scale active faults of this type will not appear on the surface. Therefore, there have been suggestions that, in addition to surface surveys based on tectonic geomorphology, comprehensive use of information on the subsurface structure may be necessary, including reflection seismic surveys, electromagnetic seismic surveys, seismic wave velocity structure, and gravity distribution. Although improvement of the Seismic Hazard Map by future surveys is awaited, even in this case, it will be necessary to resign ourselves to the possibility of earthquakes which are omitted from those assumed.

As a further problem, simultaneously with the difficulty of identifying active faults, it is also difficult to evaluate activity. Activity evaluation means estimation of the frequency of occurrence of characteristic earthquakes at individual active faults. In the case of the major active faults, information can be obtained directly by trench surveys (investigation by excavating a shallow trench), but it is extremely difficult to obtain adequate information on small-scale active faults whose positions are difficult to designate. As mentioned in the previous section, the forecast value of earthquakes of around M7 as now published is overwhelmingly smaller than their actual frequency. This may not be caused only by a failure to identify faults. Systemic problems in the earthquake occurrence probability evaluated from the activity of active faults are also a possibility. In the past, Wesnousky et al. pointed out that there is a discrepancy between the crustal movement rate at the geological time scale based on activity evaluation of active faults, and the movement rate at the scale of decades to centuries based on observations of crustal movement and seismic activity.[22] This problem still has not been solved. Although it goes without saying that information on active faults is fundamental to long-term earthquake forecasting, research from the viewpoint of explaining, without contradiction, the results of observations of seismic activity and crustal movement in recent years must not be undervalued. It would appear necessary to compensate for omissions in evaluations of active faults by unifying this type of research.

4 New research on earthquake prediction

4-1 New trends

The impact of the Great Hanshin-Awaji Earthquake was not limited to administration, but also spurred new action in the earthquake prediction researchers' group. The desire of the researchers' group to explore new approaches in prediction research coalesced in the Coordination Council for Earthquake Prediction Research in Universities, which is an organization that coordinates activities between universities and subsequently played a core role in promoting earthquake prediction research, including liaison with the administrative authorities. The direction of research which was recommended through this organization abandoned the phenomenological approach of exclusively searching for precursory phenomena followed up to that time, and returned to an approach based on physical science, which attempts to elucidate the process by which earthquakes actually occur. When the site of occurrence of one earthquake is imaged, its temporal evolution process is divided into three stages, these being a "process of stress release by the occurrence of the earthquake and recovery of a locked state," "preparatory process for occurrence of the earthquake," and "process immediately before occurrence of the earthquake." A step-by-step research strategy was delineated for each of these stages, in which the phenomena are reproduced and predicted by observation, analysis, interpretation, and simulation, and this was adopted as a roadmap for achieving prediction. A number of research groups were established by stage or by item, and a large number of research meetings and symposiums were held. Although the discoveries and results during the past 10 years have exceeded the original expectations, these are supported by the existence of the Kiban Network.

4-2 Discoveries which are key to prediction

Among the new discoveries of the past 10 years, two which are particularly important from the viewpoint of earthquake prediction are the discovery of the phenomenon of "slow slip" and recognition of "asperities." Slow slip, as the words imply, refers to a slip which occurs slowly around a fault. In contrast to true earthquakes (in the conventional sense), in which slip between plates or slip of a locked zone on a fault plane occurs suddenly in a time of several seconds to at most 1 minute, in a slow slip event, slippage continues gradually for several days or as much as several years. Slips include kinds with a variety of time constants. The existence of phenomena called “slow earthquakes” and “silent earthquakes” had be predicted previously.[23] However, this type of long-period movement is difficult to detect with conventional seismographs. Therefore, in order to capture these phenomena as facts, it was necessary to construct the Kiban Network with the GEONET, F-net, and Hi-net systems. Recently, a series of discoveries have been made, beginning with long-period slow slip events having a time constant of several years, and also including slips distributed over a wide range of frequencies, such as short period slow slips, ultra-low frequency earthquakes, low frequency earthquakes, and low frequency tremors, and it has been found that these phenomena appear in locations determined by their mutual linkage.[24]

At the same time, the existence of asperities was also demonstrated. Asperity is a key concept for understanding the slip process of locked zones. Asperities are the parts of the total locked zone on a fault plane or between plates which are locked particularly strongly. Although this concept itself had been argued since an early date,[25] the actual existence of asperities could not be detected until higher accuracy was achieved in observation techniques.[26,27] This research demonstrated that asperities are not extinguished, but rather, undergo a process of rupture and recovery of the locked state which is repeated any number of times. It has also been possible to arrive at an interpretation that, in large earthquakes exceeding M7, multiple asperities exist around the source, and differences may occur in the rupture mode in the same series of earthquakes, depending on how these asperities combine. Another idea which is continuing to gain acceptance is that a weakly locked zone exists between pairs of asperities, and that part, which had been locked in the stage of the preparatory process, slips in a quasi-static manner prior to the occurrence of an earthquake. Furthermore, actual observation has confirmed that there is a hierarchy in the sizes of asperities, and “repeating earthquakes” of M3 to M5 scale occur with high regularity at very small asperities.[28]

4-3 Promotion of simulation research

In parallel with observation, great strides have been made in computer simulations based on numerical equations which describe frictional sliding.[29] It has become possible to simulate the complex and diverse phenomena which actually occur by creating repeatedly-occurring earthquakes hypothetically on a computer and adjusting the boundary conditions. For example, it is possible to simulate repeated rupture of the same asperity, create an earthquake series with various aspects due to ruptures involving different combinations of multiple asperities, reproduce slow slip events, etc. In addition, a project aimed at creating models of the tectonics and crustal movement of the entire Japanese archipelago[30] was carried out using the supercomputer “Earth Simulator”.

The purposes of simulation research are not limited to interpretation of observed phenomena. First, a forecast of near future events is calculated by inputting observed values showing the current conditions as initial values. The various parameters defining the simulation are then adjusted by comparing the results of this forecast and the actually-observed conditions (this process is called “data assimilation”). This process is repeated and the accuracy of the forecast is improved until a practical earthquake prediction is achieved. In this manner, simulation is incorporated in the roadmap for earthquake prediction research as an indispensable technique.

4-4 Feasibility of earthquake prediction

By following a roadmap which includes the four stages of future forecasting by observation, analysis, interpretation, and simulation, earthquake prediction research has achieved steady development. Thus, it can correctly be said that the new direction of research, namely, attempting to elucidate the process by which earthquakes occur based on physical science, is bearing fruit. For example, the cyclical process of the characteristic earthquake which was discovered in the offshore area at Sanriku Kamaishi was analyzed in detail, arriving at a point where it was basically possible to predict the next occurrence.[31] Tokai-Tonankai-Nankai earthquakes occur cyclically with a period of somewhat longer than 100 years, but the pattern of occurrence of these three earthquakes is not the same each time. It has also become possible to reproduce this irregular occurrence pattern by simulation.[32]

Regarding the current status of prediction research, can it be said that research is approaching its target by following the roadmap laid out earlier? In other words, are we near the day when practical earthquake prediction will be possible? The answer is no. It is not a fact that researchers have actually succeeded in earthquake prediction. The road to universal prediction still cannot be seen.

For example, one concrete problem is "preslip." Preslip refers to a type of slip that occurs immediately before slip of the entire source area, including the rupture of the asperities at its nucleus, and starts slowly from the beginning and then gradually accelerates. Detection of this phenomenon is considered the leading candidate for advance prediction. It can be said that the expectations placed on preslip detection are one result produced by simulation research, but in fact, preslip has not been confirmed even once in actual situations. Preslip was not discovered in any of the 10 earthquakes mentioned in Table 2. Moreover, this is not limited to Japan; as of this writing, there have been no reports of the capture of preslip anywhere in the world. However, it is still early to issue a conclusion. High sensitivity instruments which are actually capable of detecting preslip have only been installed in a very small number of locations. The conditions were most favorable in the September 2003 Tokachi-oki Earthquake (M8.0), but in this case as well, the nearest tiltmeter to the source was installed more than 100km away. In the case of inland active fault earthquakes, the observation points were closer, but it is thought that preslip could not be detected due to the small size of the earthquakes themselves. As will be discussed below, prediction of a Tokai earthquake is premised on detection of preslip. However, in this case, the fact that an M8 class source will exist under the special condition of being inland contributes to the expectations that preslip detection will be possible, although with much difficulty.

In addition to the above, there is also the problem of seismic quiescence. In the verification by Prof. Wyss introduced in section 2-2, quiescence of seismic activity was recognized as the most probable precursory phenomenon.[33] Actual quiescence is related to a large number of derivative conditions, including the scale of the object background earthquake, the area and statistical significance of the quiescence, the homogeneity of the database, etc.. Therefore, the resultant quiescence information exists in a mixed state. The possibility that quiescence may be one of the few meaningful precursory phenomena is a point that many researchers acknowledge, but there is still no established theory explaining the mechanism by which it occurs. Although there are moves to interpret quiescence using the new concepts of asperity and quasi-static slip, given the current conditions, it cannot necessarily be said the research in this field is progressing.[34]

Looking at trends in scientific societies, it can be understood that a large number of researchers are not actively involved in earthquake prediction research. Figure 7 shows author's classification of approximately 600 titles presented at the 2007 Fall Conference of the Seismological Society of Japan. According to this, in excess of 50% of the titles were classified as either "Structural analysis" or "Fault model/rupture process/source mechanism." When "Geological structure/tectonics" is included, analysis on so-called spatial information totals 64%. In contrast to this, "Change in seismic activity/crustal movement/earthquake prediction," which should be called temporal information, account for only 10%. "Structural analysis" is the foundation of earthquake research, and is also the starting point of research on earthquake prediction. However, when aware of the new research strategy which has begun to investigate the various processes up to the occurrence of earthquakes by the new approach based on physical science, the current division of topics is biased, and appears to show a lack of balance. In earthquake prediction research, analysis/research on data based on long term observation and monitoring is fundamental due to the nature of the research. The recent climate that demands quick results affects researchers in their choice of topics, and there may also be structural factors that cause researchers to avoid research on subjects like earthquake prediction, for which results cannot be promised in advance.

Phenomenological prediction research has been inactive worldwide since the 1990s. Today, however, this area is continuing to produce new trends, particularly in the United States. As the object of this work is prediction of earthquakes in California, this may represent a mutual competition among individual researchers, in which researchers propose respective forecasts under the same set of conditions.[35] However, this trend has also had a ripple effect in Europe, and moves in response to these trends have begun to appear in Japan. Thus,

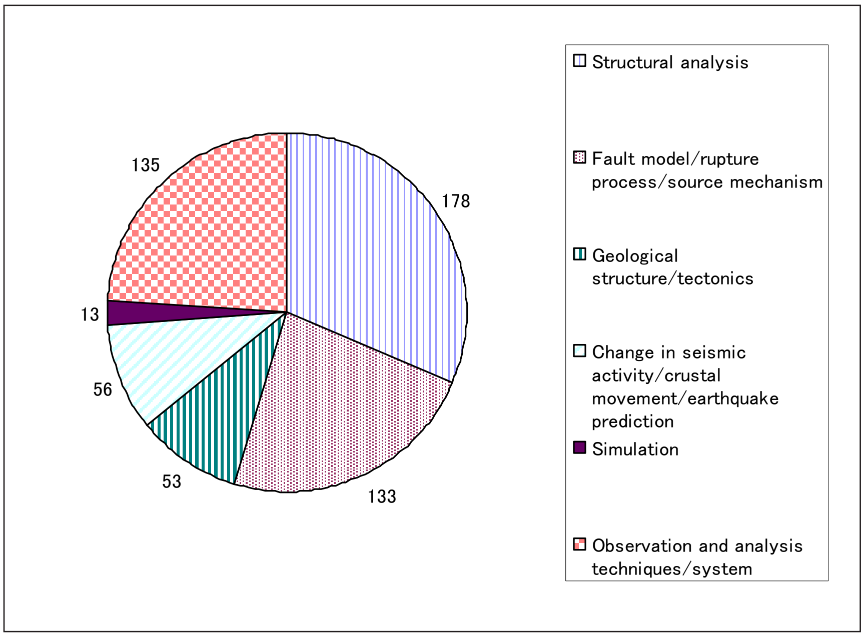


Figure 7 : Percentages of research fields judged from program of 2007 fall meeting of the seismological society of Japan

Prepared by the STFC

it may be possible to say that this is a revival of the research technique of at least attempting to extract precursory phenomena from observed events, which was rejected once in the past, against the background of new knowledge and technologies.

4-5 Prediction of Tokai earthquake

In Japan, the sole case in which the administrative authorities have acknowledged the possibility of prediction is the Tokai earthquake. In actuality, even assuming the appearance of preslip, the Tokai earthquake is the only earthquake with observation conditions that make it possible to capture this phenomenon. In March 1998, the Earthquake Assessment Committee for Tokai earthquakes revised its standard for convening, which is invoked when anomalous activity is detected.[16] If preslip is detected, the Assessment Committee will convene, based on an assumption that an earthquake will occur within 72 hours. It can be said that this is one result of progress in simulation techniques. Of course, this is ultimately only a result of simulation and is not backed by fact. Therefore, even assuming actual preslip is detected in the Tokai region, there is a remaining element of anxiety, in that the prediction based on this will itself be an “unrehearsed performance,” i.e., a prediction of a major disaster based on an unproven assumption. There are several problems, including this, which stand in the way of prediction of a Tokai earthquake.

The fact that expectations for prediction of a Tokai earthquake are placed on the appearance of preslip is based on the prior example of the 1944 Tonankai Earthquake. The day before this earthquake, an unexpected change in inclination was observed in measurements of the water level around Kakegawa.[36] However, questions were raised as to whether this observation was a true crustal movement or not.[37] Moreover, even assuming this change in inclination was actual, no convincing reason was given for the fact that the observation was made at the Kakegawa, which is located at a considerable distance from the source.

According to the forecast by HERP, the 30 year probability of a Tokai earthquake is 87% (reference value).[19] This result is based on the fact that the average interval between Tokai earthquakes, which have occurred four times since the 1498 Meio Earthquake during the Muromachi period, is 119 years. Actually, however, apart from the previous Ansei Tokai Earthquake of 1854 and the Hoei Earthquake of 1707 which preceded it, there are questions about the existence of earlier Tokai earthquakes than this, and the interval between occurrences may be longer. In other words, there is a possibility that the current probability is much smaller than that in the HERP forecast. This is also related to the suggestion that the relative velocity of the plates in the assumed source area of a Tokai earthquake may be smaller than originally assumed (4cm/yr). For example, there is a theory that part of the Philippine Sea Plate on which the Izu Peninsula rides is a microplate that has separated from the main body.[38] According to this theory, the relative velocity is assumed to be 2cm/yr, and if this is true, the interval between the occurrence of earthquakes would be two times the issued value.

Furthermore, many researchers think that there is a high possibility of linkage between Tokai earthquakes and Tonankai and Nankai earthquakes. This is because, historically, there are no examples in which a Tokai earthquake occurred independently. In the current condition, the probability of the next Tonankai earthquake is 60%. From this forecast, the crisis point should come around 2030. Assuming linkage between these earthquakes, the next Tokai earthquake will be triggered by a Tonankai earthquake, which means that its occurrence should be delayed until another Tonankai earthquake occurs.

As this discussion suggests, many difficult questions regarding the feasibility of predicting a Tokai earthquake remain unanswered. However, this notwithstanding, it can be said that the Tokai earthquake is the closest to prediction. Beginning around the year 2000, the largest slow slip in the history of observation occurred directly under Hamana Lake, which is adjacent to the assumed source, and simultaneously with this, significant changes were seen in the condition of locking in the source area. Using the dense GPS network, which is prominent even in Japan's high density observation network, it has become possible to grasp such movements in detail.[39] In other words, changes in the current condition are being captured on a moment-by-moment basis only in the case of the Tokai earthquake. Moreover, simulation research on the Tokai earthquake is gradually approaching a realistic level. Conversely, if prediction of a Tokai earthquake is thought impossible even in light of these conditions, this is equivalent to denying the possibility of earthquake prediction as such. In this sense, the Tokai earthquake must be considered a touchstone for earthquake prediction in general.

4-6 Prediction of Ibaraki-oki earthquake

On May 8, 2008, an M7.0 earthquake occurred off the coast of Ibaraki Prefecture. Here, it is known that six earthquakes have occurred virtually periodically at intervals of more than 20 years from the first historical earthquake in 1896 up to the present. Furthermore, from an analysis of the seismic waveform, it is also known that the same asperity ruptured in the most recent earthquake and the previous M7.0 earthquake which occurred in 1982.[27] It has been reported that this asperity appears to have formed with a relationship to a subducting seamount.[40] Our understanding of the Ibaraki-oki earthquakes has increased dramatically based on these facts and discoveries and the new recognition of the process by which earthquakes occur developed up to the present. Changes in seismic activity were detected before the event in this earthquake,[41,42] and there is ample reason to expect that some type of advance information will be possible when the next Ibaraki-oki earthquake arrives in about 20 years.

5 Conclusion

In "earthquake forecasting," for which the administrative authorities are responsible, a Seismic Hazard Map of Japan has been produced as the final result of a series of analytical techniques prescribed basically as manual-like procedure. If problems arise in the forecast results, this is due to inadequacy of the information used, and further study is judged to be necessary. In reality, however, the problems are not limited to an inadequate amount of information. Issues at the research level remain in the analytical techniques used in the preparation of the Hazard Map.

On the other hand, in "earthquake prediction," which has been promoted during the past 10 years based on a new direction, great progress has been made in elucidating the process by which earthquakes occur based on a physical science approach, focusing particularly on the fault rupture process. Even assuming that generalization of pinpoint prediction, as in a Tokai earthquake, is still not possible, in comparison with simple "earthquake forecasting," it may be permissible to say that "earthquake prediction" exists even today, in the sense of providing supplementary information based on analysis of stress conditions. However, this information still lacks effectiveness, and in this sense, there is a large gap between the reality of "earthquake prediction" on which researchers have fixed their gaze, and the "prediction" expected by society.

Recently, an article called “Earthquake Prediction – A Complete Change in Assumptions,” which was published by the Asahi Shimbun newspaper, reported this fact and explained in simple terms the difficulty of earthquake prediction research.[43] The author did not interpret this as a negative statement on “prediction,” but rather, saw it as an article which gave a feeling again of the strong interest of society in earthquake prediction. In other words, the motivation for prediction research is not simply the scientific interest of researchers.

The example of the Ibaraki-oki earthquake introduced in section 4-6 truly shows that, in prediction research, the level of research as a whole is frequently raised at once by the occurrence of a target earthquake. Conversely, under ordinary conditions, progress in research appears to advance slowly. If the difficulty of achieving earthquake prediction can be seen, the true nature of that difficulty lies in the fact that the results cannot be seen in advance, as is true in all creative research.

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(Original Japanese version: published in October 2008)