3

Gap Between Research and Implementation
—Prediction of Tokai Earthquake—

SHOZO MATSUMURA
Affiliated Fellow

1 Introduction

In the early morning of August 11, 2009, an earthquake with magnitude of 6.5 occurred in Suruga Bay, shaking such cities as Omaezaki and Yaizu with an intensity of 6 or lower. Since the threat of a “Tokai earthquake” had been touted for more than 30 years in Shizuoka Prefecture, many people in the prefecture thought that “it (the quake) was finally here.” Shortly afterward, however, they learned that it was not a Tokai earthquake after all, but were still concerned that the tremor may have been a precursor to a Tokai earthquake. This is a legitimate concern. However, earthquake researchers have so far been unable to produce any satisfactory answers.

In any field of science, in order to spread research results to society and see them reflected in real life, in other words, in order for research results to be put into practice, there are several steps that have to be followed, such as ascertaining the effectiveness of the research results and preparing a manual. This is why there is always a certain discrepancy between research and implementation. It may be difficult to bridge the discrepancy, but if research advances, implementation is expected to progress along with it.

In the field of earthquake prediction, however, such a scenario cannot be expected. There have been no successful examples of earthquake prediction and therefore it would be questionable to discuss the “implementation” of earthquake prediction. Generally speaking, it is extremely difficult to predict earthquakes. In previous reports, I already explained that there are no examples of earthquake prediction backed by scientific verification. However, as far as “Tokai earthquake prediction” is concerned, it without doubt falls into the category of “implementation of earthquake prediction.” So what is the current situation of “research and implementation of Tokai earthquake prediction?”

As shown in Table 1, diverse organizations are involved in Tokai earthquake prediction in their respective fields. Among them, the one that is actually engaged in earthquake prediction is the Earthquake Assessment Committee for the Areas Under Intensified Measures Against Earthquake Disaster (hereinafter referred to as EAC), which was established within the Japan Meteorological Agency in 1979. On the other hand, the Coordinating Committee for Earthquake Prediction, which was established in 1969, is a forum for researchers at universities and national research institutes. As can be seen from the fact that the predecessor of the EAC was the Tokai Earthquake Assessment Committee (Tokai EAC), which was established within the Coordinating Committee for Earthquake Prediction, there was no major separation between “research” and “implementation” of Tokai earthquake prediction. However, due to a series of unforeseen events observed in the last ten years or so, the Tokai earthquake has prompted unexpected topics of discussion. Researchers’ perception of the Tokai earthquake is no longer simple. However, it is not advisable to change the earthquake prediction system every time a new view or idea about Tokai earthquakes is published. This is because the research and implementation of earthquake prediction, which had originally been viewed from the same perspective, have gradually begun to lose touch with each other and can no longer be measured by the same yardstick. Under such circumstances, earthquake prediction is not accurately communicated to the local communities likely to be affected by earthquakes.

Table 1 : Organization and Supervisory Authority Involved in Tokai Earthquake Prediction and Their Main Role

Organization	Supervisory Authority	Main Role
Central Disaster Prevention Council	Cabinet office	Estimation of damage
Earthquake Assessment Committee for Areas Under Intensified Measures Against Earthquake Disaster (EAC)	Japan Meteorological Agency	Imminent prediction
Coordinating Committee for Earthquake Prediction	Geographical Survey Institute	Examination of observation and analysis results
Headquarters for Earthquake Research Promotion	MEXT (Ministry of Education, Culture, Sports, Science and Technology)	Current assessment/Long-term forecast
Seismological Society of Japan	Incorporated body	Research in general

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The purpose of this article is to renew the perception of Tokai earthquake prediction held by the researchers involved, by shedding light on the gap between research and implementation, and, at the same time, express our hope and expectations for their further efforts. As a starter, the background leading up to the establishment of the EAC will be reviewed in Chapter 2. Then, arguments for and against Tokai earthquake theories will be introduced in Chapter 3, newly-discovered events and phenomenon in Chapter 4, and various inferences in Chapter 5. Finally, in Chapter 6, this author would like to express his opinions about the attitudes of the researchers involved in earthquake prediction by citing the incidents of the researchers' earthquake warnings that caused turmoil in the early 2000s.

2

Evolution of Research and Implementation of Earthquake Prediction

2-1 Start of earthquake prediction system

It was the "Suruga Bay Earthquake Theory",[2] which was announced by Katsuhiko Ishibashi at the meeting of the Seismological Society of Japan in the autumn of 1976, that first prompted people to talk about a Tokai earthquake. However, Ishibashi was not the first to point out the possibility of a great earthquake hitting the Tokai region. In 1970, Kiyoo Mogi pointed out in his article[3] the possibility of a great earthquake in the Sea of Enshu. Figure 1 shows the patterns of strain in the northern edge of the Philippine Sea Plate, analyzed by the Geographical Survey Institute from differences in the measurements conducted during the Meiji era (1883-1904) and Showa era (1948-1964). It shows that the strain "expanded" in Sagami Bay, Kii Peninsula and Cape Muroto but "contracted" in the Sea of Enshu (reversed arrow in Figure 1). Mogi interpreted this to mean that the strain that had remained compressed in the former three areas was released due to the occurrence of the Great Kanto Earthquake of 1923, the Tonankai Earthquake of 1944 and the Nankai Earthquake of 1946, but that an assumed earthquake had yet to occur in the Sea of Enshu. Although Mogi's interpretation was rough compared with GPS-based observations, it was persuasive and easy to understand.

Following Mogi's article, Ishibashi compared the source area of the Ansei-Tokai Earthquake of 1854 with that of the Showa Earthquake of 1944 and found that, in the case of the latter, the asperities had yet to be ruptured in and around Suruga Bay. Based on this, Ishibashi proposed a hypothesis that the strain in the area had yet to be released and remained critical. Attaching importance to the Ishibashi theory, the Central Disaster Prevention Council in 1978 set up an assumed source area of a Tokai earthquake (rectangled area in Figure 3) in line with the Ishibashi theory and enacted "the Special Measures Law for Countermeasures Against Large Earthquakes," i.e., a Tokai earthquake countermeasures law. Prompted by the establishment of the law, the Japan Meteorological Agency inaugurated the EAC, establishing an earthquake prediction system as a national strategy.

The basis of prediction was the anomalous slope change shortly before the Tonankai Earthquake of 1944, which was excavated by Mogi (1984).[4] (Figure 2: The day before this earthquake, an unexpected change in inclination was observed in measurements of the water level around Kakegawa.) The change was interpreted as a pre-slip that occurred shortly before the Tonankai Earthquake. This idea still

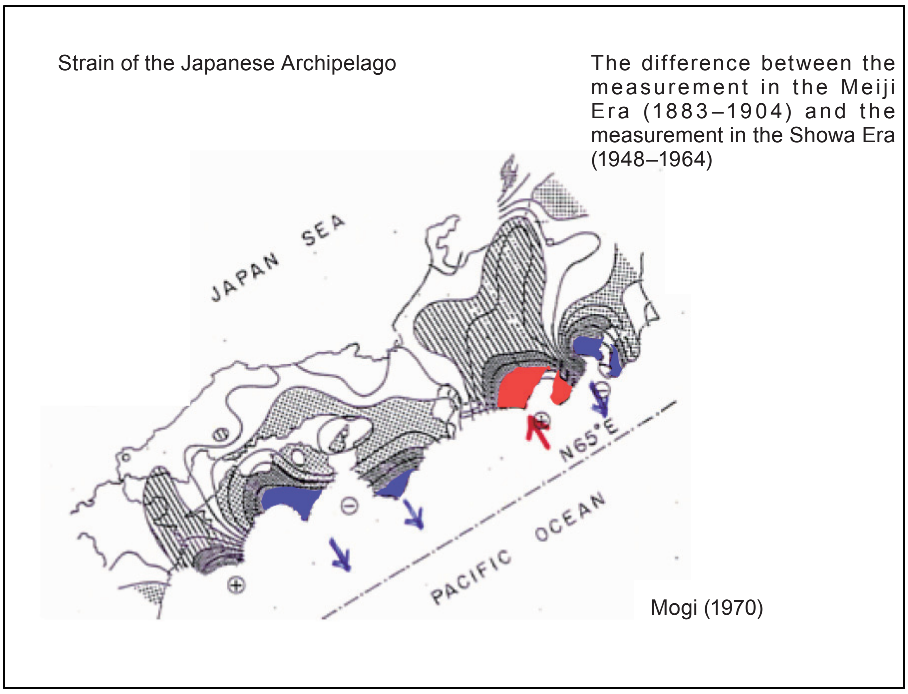


Figure 1 : Measurement of 60 Years of Strain of the Japanese Archipelago

Prepared by the STFC based on Reference[3]

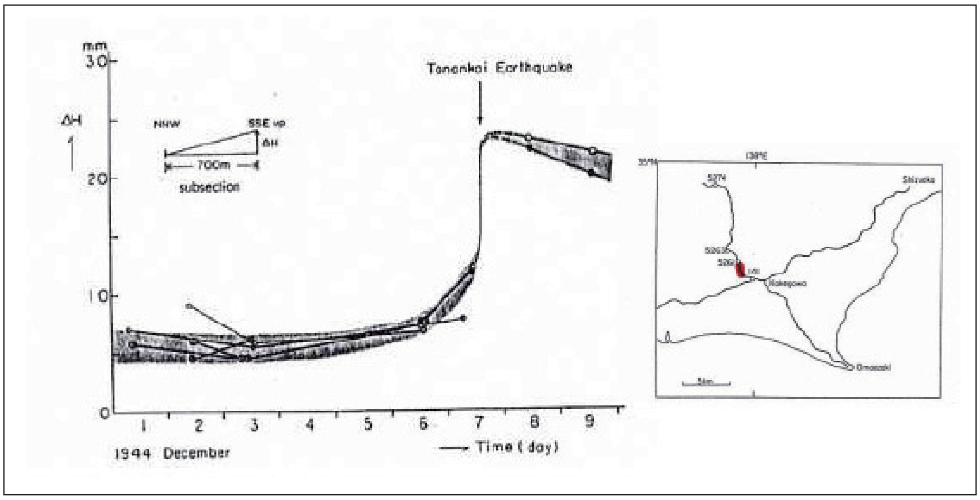


Figure 2 : Abnormal Crustal Changes Observed Shortly Before the Tonankai Earthquake Around Kakegawa, Shizuoka Prefecture

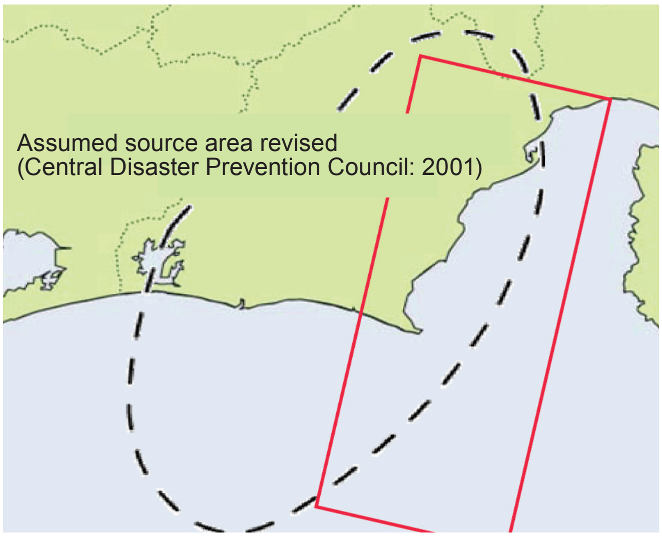
Source: Reference[4]

forms the pillar of the Tokai earthquake prediction strategy.

As described above, Japan has come to take national measures for earthquake prediction by establishing laws. This is thanks to the fact that the announcement of the research results and the contents of the indications and warnings based on research results were explicit, simple and easy to understand. This is an example of research results leading to actual practice. As will be described below, the results of Tokai earthquake research were reflected in actual prediction strategies at least twice.

2-2 Revision of Assumed Source Areas

When Ishibashi proposed the Great Suruga Bay Earthquake Theory, there were no sufficient observation data to support the theory. However, after the law was established, the observation system in the Tokai region made outstanding progress. For instance, the subduction of the Philippine Sea Plate under Shizuoka Prefecture, which was not initially detected, has come to be clearly reflected in micro-seismic activity data. Also, the GPS observation



The rectangle area is the first assumed source area based on Ishibashi theory. The area with the broken line is the newly established source area.

Figure 3 : Assumed Source Area Revised

Prepared by the STFC based on Reference[5]

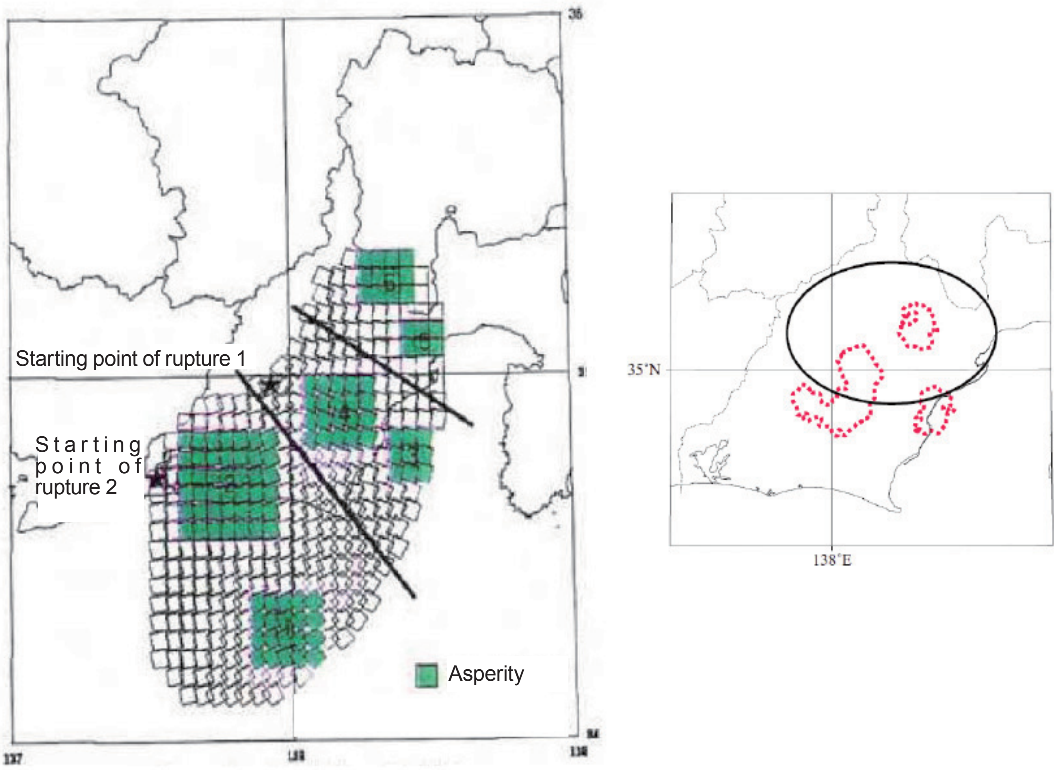


Figure 4 : Asperities Assumed by the Disaster Prevention Council (six rectangles in the left chart) and Asperities Estimated From Observation Data (three circled areas in the right chart) (The ellipse in the right chart is an area with strong ground motions in past Tokai earthquakes.)

Prepared by the STFC based on Reference[5,32,33] network (GEONET), which was established by the Geographical Survey Institute, has made it possible to monitor in real time the process of crustal strain caused by the subduction of locked zones. Based on these new observations and analysis results, the Central Disaster Prevention Council in 2001 revised the assumed source areas of the Tokai earthquake for the first time in 23 years[5] (heavy broken line in Figure 3 and eggplant-shaped line in the left graph in Figure 4). The revision was made possible as the locked area on the surface of the Philippine Sea Plate came to be depicted in a more practical manner from data on microseismic activity and crustal movement. Furthermore, the Council worked out the estimates of seismic intensity and damage by assuming six asperities (parts of asperities between plates that are locked strongly; rectangles in the left graph in Figure 4) in the assumed source area and, based on them, revised the areas under intensified measures against earthquake prediction. However, the assumed asperities were determined artificially, based on an intensity prediction manual, and therefore are not based on observation and analysis results, as will be discussed later.

2-3 Revision of Standard for Convening EAC Meeting

When the Earthquake Assessment Committee was established, the standard for convening an AEC meeting was also established; and in 2004, the standard was modified (Osamu Kamigaichi/Shinya Tsukada, 2006).[6] Earthquake information to be issued by the Japan Meteorological Agency is classified as an earthquake report, earthquake advisory or earthquake warning, depending on the extent of crustal deformation. Of the three categories of information, the earthquake advisory information, which will be issued when strainmeters in two different places detect anomalous changes at the same time, is practically the standard for convening an EAC meeting. The difference between the previous standard and the modified standard for convening an EAC meeting is that while the previous standard required anomalous changes in both crustal movement and seismic activity, the new standard has abolished the requirement of anomalous seismic activity. This is because, although seismic activity provides a greater variety of information than crustal change, it is difficult to provide a unique interpretation of ongoing phenomenon from seismic activity. In other words, since the decision of whether a phenomenon is abnormal or not differs from one person to the next, it is not appropriate to use seismic activity as a criterion to govern people's behavior according in an emergency manual. This is one of the problems lying between research and implementation of Tokai earthquake prediction.

Meanwhile, the standard for convening an EAC meeting based on anomalous crustal changes has been further strengthened. This is partly because the detection capability has drastically improved thanks to an increase in the number of borehole strainmeters installed and the advance made in analysis technique. The development of a simulation technique for pre-slip analysis has also greatly contributed to the stricter standard. According to a two-dimensional model developed by Naoyuki Kato and Tomoo Hirasawa (1996),[7] the time from a pre-slip event to a final breakage is far shorter than previously expected. Based on this, the conventional threshold for anomaly detection has been lowered to one-tenth.

3 Questions About Tokai Earthquake Theory

The Tokai Earthquake Theory, which was once supported without a doubt, has raised several questions 30 years after its publication. Some people question the scenario of the theory itself.

3-1 Linkage of Nankai Trough earthquake series (Denial of independent occurrence of Tokai earthquake)

According to a list of long-term estimations of the probability of active fault or inter-plate earthquakes,[8] which was published by the Earthquake Research Committee under the Headquarters for Earthquake Research Promotion in Table 1, the probability of an M8-class Tokai earthquake occurring within 30 years from 2009 is 87% (reference value). This is based on the fact that the average interval of the past four Tokai earthquakes (Meio Earthquake of 1498, Keicho Earthquake of 1605, Hoei Earthquake of 1707, and Ansei Earthquake of 1854) is 118.8 years. The probability of a Tokai earthquake is listed only as a reference value. This is because, unlike Tonankai

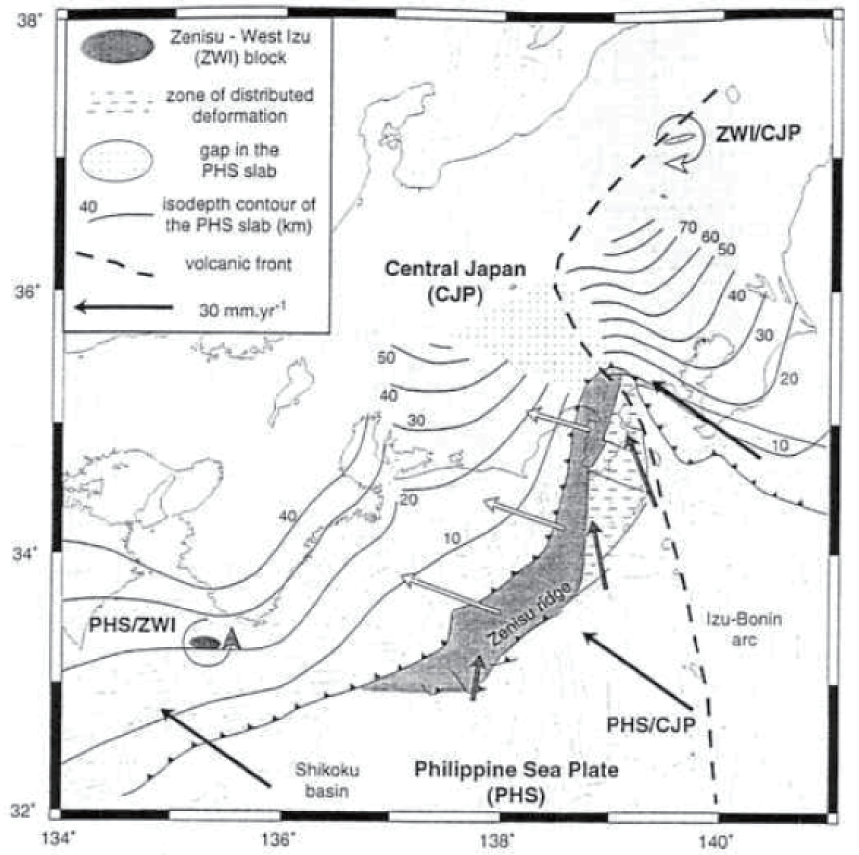
Earthquakes (M8.1; occurrence probability of about 60–70%) and Nankai Earthquakes (M 8.4; occurrence probability of about 50–60%), the nature of the older earthquakes, such as the Meio and Keicho earthquakes, is not clear, and it is not known whether the damage of the quakes extended to Suruga Bay (Ishibashi, 1981).[9]

In order to obtain historical records of past earthquakes, researchers first turn to ancient documents. However, ancient documents do not necessarily cover every earthquake and disaster. Akira Sangawa[10] has devised a method to speculate on the occurrence of past earthquakes from traces of liquefaction discovered in archaeological sites (earthquake archeology) and succeeded in covering some of the Tonankai and Nankai earthquakes that were missing in ancient documents. There are also cases where traces of large inter-plate earthquakes were discovered from tsunami deposits in the bottom of ponds and lakes near sea shores. These discoveries have made it clear that, as far as Tonankai and Nankai earthquakes are concerned, they occurred on a regular basis. On the other hand, past occurrences of Tokai earthquakes are not clear. If we suppose that the average interval of Tokai earthquakes is about 100 years, the probability of a Tokai earthquake occurring would come to be excessively high. Moreover, historical records show no examples in which a Tokai earthquake occurred independently from Tonankai and Nankai earthquakes. Even in simulation research, which will be discussed later, it is said to be difficult for a Tokai earthquake to occur independently. If we assume that a Tokai earthquake does not occur independently, its occurrence probability cannot be higher than those of Tonankai and Nankai earthquakes. To look at it another way, a Tokai earthquake will not occur in the next 10 to 20 years, or until the next Tonankai earthquake.

3-2 Assessment of Relative Velocity of Plates and Izu Microplate Theory

Is the Earthquake Research Committee's claim that "the average occurrence interval between Tokai earthquakes is about 120 years" realistic? The key to this question is the relative velocity of the Philippine Sea Plate, which is moving below the Eurasian Plate in Shizuoka Prefecture from Suruga Bay. For instance, if calculated by using a plate model developed by Tetsuzo Seno (1993),[11] the Philippine Plate is moving N50 degrees W at a velocity of about 40mm/yr. If it continues to move at this speed, the "relative slip" accumulated in 120 years will come close to 5 meters, enough to cause an M8 earthquake. Incidentally, the accumulated slip (relative slip) caused by an M8 earthquake calculated by the Matsuda formula (Tokihiko Matsuda, 1975),[12] which is used in calculating active fault earthquakes, comes to 6.3 meters, and the average amount of slip caused by the Ansei-Tokai Earthquakes (M8.4) estimated by Ishibashi[9] is 4.0 meters. However, some researchers have come up with a theory that the motion of the Philippine Sea Plate near Shizuoka is not that simple. Mazzotti et al. (1999)[13] maintain that the northern tip of the Philippine Sea Plate, including Izu Peninsula, has been separated from the main body and is moving independently (shaded area in Figure 5). If this theory is adopted, the relative velocity of the plate in Suruga Bay will come to 20–25mm/yr at most, and it would take 160–200 years for the slip to accumulate to 4.0m.

In order for the strain under Shizuoka Prefecture to have already reached its expiration period, the relative velocity of the plate has to be at least 30mm/yr. However, it is difficult to measure the movement of plates. One of the methods of solving this problem is "backslip analysis," which seeks to understand the motion of underground plate boundaries from crustal changes on the ground surface. Although several reports have already been released on the results of backslip analyses, the value of relative velocity obtained from the method varies widely from 20mm/yr to 40mm/yr depending on the data and calculation technique used. The median value of the results is about 30mm/yr. However, the method of the backslip technique itself is being called into question and the reliability of the results is not sufficient. Meanwhile, the relative velocity of the Philippine Sea Plate is also estimated from the information on low-frequency tremors and short-term slow slips occurring in areas deeper than the locked areas that have come to be analyzed in detail. According to Akio Kobayashi et al. (2009),[14] the relative velocity of the plate under eastern Aichi Prefecture in and after 2000 is 39–49mm/yr, while Kazushige Obara (2009)[15] estimates the velocity in the same area in and after 2004 at 43mm/



The shaded area is assumed to have been separated from the Philippine Sea Plate and is moving independently.

Figure 5 : Izu Microplate Proposed by Mazzotti et al.

Source: Reference[13]

yr. They are close to or slightly faster than the theoretical speed calculated by Seno 11). Moreover, Makoto Matsubara et al. (2006)[16] estimates it at 30–40mm/yr based on the amount of slip of similar earthquakes (earthquakes of similar wave shapes regardless of their magnitude) detected beneath Lake Hamana.

All of this information suggests that the cycle of Tokai earthquakes is ambiguous. All we can say at present is that it ranges from 100 to 200 years.

3-3 Questions About Crustal Deformation in Kakegawa

As described in Chapter 2-1, the only evidence supporting the possibility of a Tokai earthquake prediction by the EAC is the abnormal crustal tilt discovered in Kakegawa City shortly before the Tonankai Earthquake of 1944. However, some researchers disputed the survey results. At the meeting of the Seismological Society of Japan held in autumn 2004, Takeshi Sagiya (2004)[17] said, “Although a crustal deformation may have occurred shortly before the earthquake, we cannot rule out the possibility that the deformation was simply the result of mistakes in surveying.” If the abnormal tilt is caused by a true crustal change, there must have been a pre-slip event. However, although a highly sensitive observation network has been established in recent years, there have been no reports that a pre-slip event was detected shortly before the occurrence of a big earthquake. Even in up-close observations of minor earthquakes in a gold mine in South Africa, which is being conducted by Ogasawara et al. (2009),[18] no pre-slip has been discovered. So far, the existence of a pre-slip has been confirmed only in observation in laboratories and in simulation. However, it does not mean that the pre-slip of the Tonankai Earthquake has been ruled out. Linde and Sacks (2002)[19] claimed that, if about 2 meters of slip is assumed at the deeper extension of the source area, the abnormal tilt in Kakegawa City can be explained, suggesting that the abnormal tilt change may have been caused by a pre-slip.

As can be seen from the above, that aspect of the last Tonankai Earthquake is significant in predicting the next Tokai earthquake. However, there are still disputes with regard to the source area of the Tonankai Earthquake and to what extent the eastern edge of the Tonankai Earthquake, which borders a Tokai earthquake, had extended. With regard to the extension of the source area of the Tonankai Earthquake of 1944, nearly ten models have been proposed, including one by Hiroo Kanamori (1972),[20] but none of them has proved conclusive. Depending on the results of model analysis, the existence of a Tokai earthquake itself will become uncertain. Sagiya (2007)[21] argues that, in order to explain the results of leveling conducted across the source area, it is necessary to assume that a slip took place in the spray fault near Kakegawa City, not in the plate boundary. Although this argument does not deny the existence of pre-slips, it has raised questions again about the ambiguous identification of the ruptured area of the Tonankai Earthquake and, by extension, the existence of the Tokai earthquake itself.

4 Current State of Crustal Activity in the Tokai Region

Here, I would like to enumerate events that were discovered in the Tokai region in the last ten years or so and outstanding or abnormal activities.

4-1 Seismic/volcanic activities

(1) In October 1996, an M4.3 earthquake occurred under Kawane town (now Shimada City), Shizuoka Prefecture. Although the earthquake was not big, the fact that it was an inter-plate earthquake prompted questions about its relationship with a Tokai earthquake.

(2) In the locked area of Tokai earthquakes, the activity of seismogenic layers above and below the plate boundary has been showing signs of quiescence since the second half of the 90s, raising disagreements over its relationship with a slow slip (Matsumura, 2002).[22] In particular, minor seismic activity was detected directly under Shimada City, and a group of similar earthquakes was discovered there (Matsubara et al., 2006).[16]

(3) From June to August 2000, a series of earthquakes, including an M6 earthquake, occurred in the area surrounding Miyakejima, Niijima and Kozushima islands. At the same time, volcanic activity began on Miyakejima Island, leading to a major eruption accompanied by caldera formation for the first time in 17 years. The seismic activity came to an end in August 2000 after causing earthquakes generated by magma intrusion and the ones generated by shear rupture in the plate. In September of the same year, however, low-frequency earthquake activities increased under Mt. Fuji.

(4) In September 2004, an M7.4 earthquake occurred at the offshore area southeast of Kii Peninsula. Although the epicenter was near the Nankai Trough, it was not an inter-plate earthquake that caused the Tonankai earthquakes but an intra-plate earthquake in and above the Philippine Sea Plate. Due to this earthquake, a wide area from Shizuoka Prefecture to Mie Prefecture moved southward. Although it is difficult to assess the impact of the quake on Tokai earthquakes (Seno, 2006),[23] the non-stationary earthquake that occurred near the axis of the trough may be a precursor of an inter-plate earthquake.

(5) In a narrow band area extending from Shikoku, Kii Peninsula to Ise Bay and southern parts of Aichi and Nagano prefectures, where the Philippine Sea Plate has subducted 30–40km deep, Obara (2002)[24] and Noritake Nishide et al. (2000)[25] discovered what is called “low-frequency tremor” or “low-frequency earthquake” activities that are different from normal earthquakes. Although similar phenomena were also discovered in North America, such activities do not occur in all plate subduction areas. For example, no such activities have been discovered in the Pacific Plate. It has been speculated that such activities may have something to do with the water dehydrated from subducting rocks. Later, it was discovered that lower frequency earthquakes (deep ultra-low frequency earthquakes) are occurring at the same time (Yoshihiro Ito et al., 2007).[26]

(6) Aside from the deep ultra-low frequency earthquakes mentioned in (5), it is known that “shallow ultra-low frequency earthquakes” occur in shallow areas near the trough axis. They are speculated to be earthquakes occurring on the spray faults rising from the plate boundary (Ito/Obara, 2006).[27]

(7) Early in the morning of August 11, 2009, an M6.5 earthquake occurred in Suruga Bay off

Shizuoka City (as mentioned in the Introduction). The quake erupted inside the Philippine Sea Plate, indicating that the mechanism of the quake was different from the Tokai earthquakes. It may be one of the M6 class “Shizuoka earthquakes” that occur in and around Shizuoka City at intervals of about 40 years. However, there are also concerns that it may trigger a Tokai earthquake.

4-2 Crustal movement

The Geographical Survey Institute has been operating its nationwide GPS observation network (GEONET) since the second half of the 1990s and has discovered movements that are different from previous movements in the area centering on Lake Hamana. An inverse analysis revealed that a slow slip against the plate movement was happening in the plate boundary under Lake Hamana. The slip continued until around 2005 and amounted to about 25cm in the center of the fault, meaning that about ten years’ worth of plate drag was released. Based the discovery, Eiji Yamamoto et al. (2005)[28] studied past tilt data and Kobayashi et al. (2004)[29] studied past tidal data, and both found that a similar slip has been repeated at intervals of about ten years. This can be seen as a kind of earthquake in that the fault, which is usually locked, is sometimes unlocked and slips, albeit slowly.

Meanwhile, in the inner part of the further subducted plate, low-frequency tremors, low-frequency earthquakes and deep ultra-low frequency earthquakes that were mentioned in the preceding section, had been discovered. However, they were found to have been caused by feeble slips on the plate boundary, or, in other words, by slow slips. These slips stop after several days and repeat at intervals of about six months, while the slow slips mentioned in the previous section last for several years. The former is called a short-term slow slip and the latter is called a long-term slow slip. Although the existence of such slow slips had been forecast by Ichiro Kawasaki (2006),[30] the phenomena that were actually observed showed far more diverse aspects than had been forecast.

4-3 Subsurface structure

There is no longer any question about the observed fact that the locked areas of the Philippine Sea Plate have been subducting under the Tokai region. However, when it comes to their microstructures, it is still open to dispute. With regard to the shape of the Philippine Sea Plate, several models have been presented, but there are no major differences among them. Still, in some cases, even a minor difference has become a point in dispute. For instance, there is dispute about the depth of the plate boundary under Hamaoka Nuclear Power Plant in Shizuoka Prefecture, with the depth estimated by the models ranging from 10km to 20km. The dispute has yet to be settled. There is also an argument that the actual subduction of the Philippine Sea Plate starts not in the Suruga Bay but runs through the bottom of Izu Peninsula to Sagami Bay. There are several methods for exploring the geometry of the fault system, such as explosion seismic experiments and special analytical methods using seismic waves (including receiver function analysis). However, such surveys in Suruga Bay have yet to produce tangible results.

In the Sea of Enshu, on the other hand, a reflection survey has been under way and it has produced results. In the area under Omaezaki, it was discovered that the upper part of the subducting Philippine Sea Plate has bulged. Shuichi Kodaira et al. (2003)[31] speculated that the bulge was due to the subduction of one of the rows of corrugation on the sea bottom along the Nankai Trough. While the corrugation in the area off the Sea of Enshu is called the Zenisu Ridge, the one below Omaezaki is called the “old Zenisu Ridge.” And it is speculated that there may be an “old-old Zenisu Ridge” in an area further away from the direction of the plate movement. In either case, it is widely accepted that the topographical undulation of a plate boundary causes a concentration of strain, leading to the formation of asperities of inter-plate earthquakes.

4-4 Summary of events

Figure 6 is an overview of the events described the preceding sections. The anomalous events mentioned in Section 4-1 ((1) earthquake in central Shizuoka Prefecture, (2) similar earthquake clusters, (3) a series of earthquakes in the area surrounding Miyakejima, Niijima and Kozu islands, (4) earthquake in the area southeast of Kii Peninsula, (5) low-frequency earthquake (low-frequency tremor), (6) shallow ultra-low frequency earthquakes, and (7) Suruga Bay earthquake), and those mentioned in Section 4-2 ((8) long-term slow slip and (9) short-

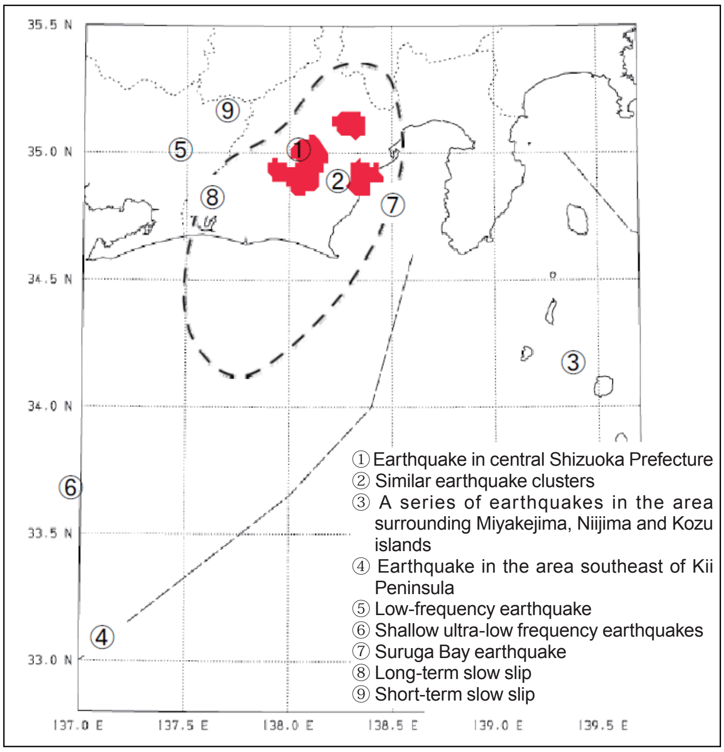


Figure 6 : Abnormal Occurrences and Newly Discovered Events in the Tokai Region in the Last Ten Years(Dashed line is the assumed focal zone of the Tokai earthquake, with the three silhouetted areas indicating assumed asperities.)

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term slow slip) occurred in or around the assumed source area and the assumed asperities (the three shaded areas).

The long-term slow slip in (8) develops on the edge of the assumed source area, while the short-term slow slip in (9) develops in the deeper parts of the area. And in the deeper areas, the plate is probably slipping without being locked. Although both (1) earthquake in central Shizuoka Prefecture and (2) similar earthquake clusters are recognized as being unusual inter-plate earthquakes, their locations are regional. The effects of those earthquakes ((3) the series of earthquakes near Miyakejima Island and (4) earthquake in the area southeast of Kii Peninsula) are not clear. However, judging from the fact that the two earthquakes occurred close to the start and end of their respective slips, they may have worked to control the slips in one way or another.

As seen from the above, events that were newly discovered in the last ten years or so are concentrated in and around the assumed source area of Tokai earthquakes. The discovery of some of the events was made possible thanks to progress made in observation techniques. Still, there are no examples of such a concentrated occurrence of events in any other region. Regardless of whether it is in a critical condition or not, there is no doubt that the Tokai region's situation is anomalous.

5 Various Inferences

Several inferences, though far from comprehensive, have been made with regard to the events discovered thus far.

5-1 Assumption of asperity

When the assumed source area of a Tokai earthquake was revised, asperities were assumed in order to predict damage, as is shown in the left graph of Figure 4. The assumption is based on the manual for predicting ground motion. Although the number of asperities in the graph may appear to be slightly excessive at six, it is a reasonable number of asperities for predicting damage in the worst case. Still, in order for earthquake prediction to be practical, assumed asperities must be based on facts. This is because, when an abnormal crustal movement is detected, having as realistic an impression of asperities as possible is indispensable for discriminating a pre-slip. Therefore, it is necessary to provide practical asperity information based on observed data. The author et al. (2008)[32] identified three strain-concentrated areas in central Shizuoka Prefecture from a strain distribution measured by changes in seismic activity and the GPS network, and assumed them to be asperities (the right graph in Figure 4). On the other hand, Katsuhisa Kanda et al. (2004)[33] located strong ground motion at the time of the Ansei-Tokai Earthquake of 1854 from records of damage caused by the earthquake. They also located similar motion at the time of the Hoei Earthquake of 1707. The oval in the right graph of Figure 4 shows that the areas with the strong ground motion caused by the two earthquakes are located at almost the same spot in central Shizuoka Prefecture. It is almost the only information indicating the locations of the asperities of the past Tokai earthquakes. It also shows that the locations almost correspond with those of the assumed asperities in the graph.

5-2 Simulation

Since the information obtained from the Ansei-Tokai Earthquake of 1854, which was the latest Tokai earthquake, is limited, it is almost impossible to check if the information on the events enumerated in Section 4-4 was available in those days. In that sense, we will know the whole picture of Tokai earthquakes and their crustal movement only after the next Tokai earthquake occurs. And the experience we have from the next earthquake will become useful in predicting the earthquake after that. But in the meantime we can’t sit idly and do nothing. Therefore, we need to utilize simulation techniques to create a virtual Tokai earthquake on a computer and observe in detail the process by which an earthquake is generated.

As a basic equation for simulations, the friction law proposed by Ruina (1983)[34] is widely used. According to the law, it is possible to simulate an alternate, cyclic appearance of a slow process of stress accumulation between earthquakes and high-speed slippage at the time of an earthquake, by simply running two differential equations.

For instance, the new standard for convening an EAC meeting, which was discussed in Section 2-3, is based on the results of two-dimensional simulations conducted by Kato and Hirasawa (1996).[7] The revision of the standard is based on the pre-slip and its configuration by computer simulation. Takane Hori et al. (2006)[35] ran three-dimensional simulations of Tokai, Tonankai, and Nankai earthquakes along the Nankai Trough and found that there is a certain pattern in the way earthquakes occur if the cycle and order of earthquake occurrences are adjusted to actual conditions in simulation. As a result, they showed that it is difficult for a Tokai earthquake to occur independently. Fuyuki Hirose et al. (2008)[36] developed a Tokai earthquake simulation by using more practical three-dimensional plate models. The simulation reproduces a long-term slow slip under Lake Hamana. In order to reproduce slow slips in simulation, it is necessary to minutely adjust parameters. Shingo Yoshida and Naoyuki Kato (2002)[37] were the first to succeed in simulating a slow slip. Bunichiro Shibasaki and Bu Shuhui (2007)[38] have succeeded in producing both short-term and long-term slow slips simultaneously. What is interesting is that the results of any of the simulations will show the repetition of a long-term slow slip several times before the occurrence of a Tokai earthquake.

5-3 Judgment of critical condition

As mentioned in Section 3-2, it remains ambiguous whether the occurrence of a Tokai earthquake is in a critical state or not. In order to assess it, it is necessary to know to what extent the stress and strain that have been accumulated so far are close to their limits. However, although we can estimate the annual accumulation of stress and strain, it is impossible to know the absolute value of the stress that has already been accumulated. In the circumstances, a method to diagnose stress from seismic activity’s dependence on the tide is drawing attention. Sachiko Tanaka et al. (2002)[39] surveyed seismic activities in subduction zones around the world and discovered the effect of the tide on the small earthquakes that occur before a big earthquake in subduction zones. It may sound strange that a tidal stress of only several KPa influences an earthquake that releases several MPa of stress. However, it is understood that, when the stress is in a critical state, the tide can give one final push. Furthermore, Tanaka et al. (2004)[40] surveyed the dependence of microseismic activities on the tide and selected ten high-dependence areas. In four of them, earthquakes with an intensity of M6 or higher already occurred. The Tokai area is one of the six remaining areas.

5-4 Nankai Trough earthquake series in the Showa era

As mentioned in Section 3-1, the Nankai Trough earthquake series is basically characterized by its "linkage." In the previous Showa series, Tonankai and Nankai earthquakes occurred at intervals of two years. In the Ansei series, which preceded the Showa series, Tokai and Tonankai earthquakes occurred concurrently followed by a Nankai earthquake one day later. In the Hoei series, which preceded the Ansei series, the three earthquakes occurred concurrently. Then, why was it only the Tokai earthquake that did not occur in the Showa era? Pollitz and Sacks (1995)[41] claim that the Nobi Earthquake of 1981 (M8.0), which was one of the largest active fault earthquakes, had something to do with it. According to their model calculation, while the stress redistribution caused by the Nobi Earthquake sped up the occurrence of the Tonankai Earthquake, it delayed the occurrence of a Tokai earthquake by about 20 years. Setting aside the question of numerical evaluation, what they argue is that the Nobi Earthquake upset the linkage cycle of only the Showa earthquake series. If this idea is expanded, it means that Tokai earthquakes belong to the Showa series, making it difficult to rule out the possibility of a Tokai earthquake occurring independently. At this stage, it is going too far to place a disproportionate emphasis on the judgment premised on a linked occurrence of Tokai and Tonankai earthquakes.

5-5 Current state of stress concentration

It appears that the long-term slow slip under Lake Hamana occurred repeatedly at intervals of about ten years. The latest slow slip, which started in around 2000, appears to have come to a halt in around 2005. For this reason, we can conclude that it was one of those slow slips that are forecast to occur several times before a Tokai earthquake. However, closer examination showed that the slip did not stop completely. It started again in 2007, albeit slowly, moving from Lake Hamana to southern Nagano Prefecture and eastern Aichi Prefecture. At around the same time, micro earthquakes became active in western Shizuoka Prefecture (Matsumura, 2009).[42] Figure 7 shows the movement of the slow slip starting around Miyakejima Island in 2000 to the areas surrounding the assumed asperities (Kobayashi et al. (2005)[43] and the Geographical Survey Institute (2009)[44]).While the speed of the slip has slowed down as a whole, this can be interpreted to mean that the locking of plate boundaries surrounding the group of asperities is almost complete. Seismic activities indicate that the stress concentration on asperities has increased more than ever. Therefore, we cannot conclude that the latest slow slip is simply a repetition of past slip events.

6 Role of Researchers

In the early 2000s, researchers published a series of warnings about the occurrence of a Tokai earthquake. George Igarashi (2000)[45] paid attention to a gradual decrease in the vibration period of a critical physical phenomenon and concluded that a Tokai earthquake would occur in mid-2004, judging from the vibration of the leveling data between Kakegawa and Hamaoka. Kawasaki and Okada (2001)[46] claimed that a Tokai earthquake would occur in early 2001 by working out a theoretical equation on the growth of nucleation and applying it to the leveling data between Kakegawa and Hamaoka. Koshun Yamaoka et al. (2001)[47] conducted

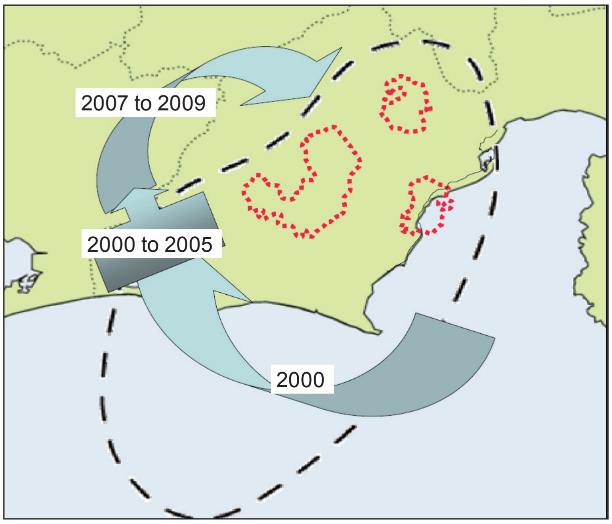

Figure 7 : Movement of slow slip surrounding assumed asperities (circled by a dotted line) in the assumed source area

Prepared by the STFC based on Reference[43,44] a time-to-failure analysis of the movement of the GPS installed in Hamaoka and speculated that it would come to a critical stage in mid-2002. Seno (2003)[48] developed a model for the process of a change in asperity distribution and estimated that a Tokai earthquake would occur in mid-2007, judging from the data between Kakegawa and Hamaoka. The author (2002)[22] estimated that the accumulated stress would reach its limit in around 2006, judging from the size of the assumed asperity area. The announcement of these speculations about the time of the occurrence of a Tokai earthquake, which came around the same time, drew the attention of the mass media and the Internet and caused public tension at the time. However nothing happened and the estimated time they set for the occurrence of a Tokai earthquake passed.

In hindsight, these warnings ended in failure in that no Tokai earthquake occurred. However, since the author himself was involved, I would like to discuss the advisability of such warnings by researchers. First of all, was it just a coincidence that the researchers announced earthquake warnings at around the same time, or were there events that prompted them to make the warnings? Yes, there was an abnormal situation. It was a long-term slow slip, which was described in the preceding sections. After all, it may be concluded that the latest slow slip was just one of the slow slip events that have been observed time and time again in the past. Even so, it is nothing but an afterthought. I think that it was reasonable for researchers to issue a Tokai earthquake warning at the start of a slow slip event. I would venture to say that, with our current knowledge, it was a little bit of a stretch for us to specifically mention when an earthquake would occur. I should add that there still remains a possibility that the above warnings will come true.

The incident may have been a bitter experience for the researchers involved. Rather, I'm worried that, after this thing, they become cautious about expressing what they have inferred from their research. At present, presentations made at academic society meetings are mostly reports on observed events or the results of data analyses. Aside from inferences that are logically derived from analysis results, other inferences tend to be rejected as speculation ("empty theory" or "conjecture"). This is because, while fact verification and situation analysis are the base of a science-based approach, speculations intermixed with forecasts could be misleading as they contain ambiguity. However, if researchers are preoccupied only with reporting established facts, it will not lead to practical earthquake prediction.

I think that researchers involved in earthquake prediction should always be open to making forecasts. When they analyze an event, they should not stop at just the analysis but should speculate on what it means and predict its future. For instance, take the Kii-hanto Nanto-oki Earthquake, which was taken up in Section 4-1 (4). With this earthquake, there are many reports on its characteristics and how it occurred, but there are few discussions on how it will affect the future occurrence of Tokai and Tonankai earthquakes. As Seno (2006)[23] said, it is difficult to judge even whether its impact on future earthquakes is positive or negative. Having said that, however, I do not mean that they should come up with a decisive conclusion. Rather, I am saying that they should present their inferences and conduct lively discussions on them.

As a model case, I would like to introduce a workshop dubbed "Thorough Debate—Where Will the Next Tokai Earthquake Occur?"[49] held at Nagoya University in January 2007. More than just a workshop, it was an unusual panel discussion in which five researchers presented their research results and exchanged views on several topics in order to coordinate their perceptions. Although the panelists were unable to reach a conclusion on when a Tokai earthquake would occur, it was refreshing to see them present challenges and discuss them.

Some have proposed that such workshops should be organized under the leadership of academic societies. It could be pointed out as a good proposal. But what I am really calling for is action that should be taken before that. Nobody can say for sure what is forecast. Even so, researchers should be able to let their imaginations run on what they have researched and draw inferences from it. It doesn't matter whether they can reach a consensus or not. What is important is that there should be diversified inferences and lively exchanges of views on them and that the public should be informed of the process of such discussions.

Any prediction or forecast of an earthquake, however simple it may be, may eventually prove to be wrong. The researchers should be aware of that and be prepared to take on criticism for making a wrong prediction or forecast. I hope that researchers of the Tokai earthquake, or earthquake prediction in general for that matter, will be prepared for that as their role.

7 Conclusion

One day after the “Suruga Bay Earthquake of 2009,” Japanese newspapers wrote in their editorials about Japanese measures against a Tokai earthquake. Among them, Nihon Keizai Shimbun was critical of the Earthquake Assessment Committee system, saying that “we should not be overly swayed by the assumptions or hypotheses that are decided by the administration or academic society without scientific verification.” Admittedly, the current earthquake prediction, which is premised on the appearance of a pre-slip, is not scientifically verified. However, it does not mean that the existence of a pre-slip has been rejected. It is not wrong for the EAC to base its prediction of a Tokai earthquake on the appearance of a pre-slip. The EAC once insisted that it would never overlook any signs of an earthquake. However, after the serious disaster by 1995 Kobe Earthquake, the EAC brought down its tone and now says that it may overlook even a Tokai earthquake. Therefore, people are well aware of the danger of totally relying on earthquake warnings issued by the EAC. Under such limited conditions, the EAC system is relevant to today, even if its probability of successful prediction is less than 50%. Rather, the problem is that people misunderstand that everything about Tokai earthquake prediction is left to the EAC. Judging from the fact that researchers are not active in making presentations on a Tokai earthquake at academic meetings, even researchers seem to have a similar misunderstanding. Given the complicated situation of the Tokai region, the scope of judgment allowed for the EAC is extremely limited. Regarding the latest Suruga Bay earthquake, the EAC issued a comment, saying that it “has no direct relationship with a Tokai earthquake.” Since the role of the EAC is limited to making predictions of a Tokai earthquake, the comment seems appropriate. However, it will not satisfy the public. While they are well aware that the EAC’s prediction is always vague and sometimes misleading, they still want to know how a Suruga Bay earthquake relates to a Tokai earthquake. Researchers are required to make their own inferences based on the knowledge and power of judgment they have built up. From the viewpoint of “the gap between research and implementation concerning the prediction of a Tokai earthquake,” researchers, who are in a different position from the EAC, have a big role to play.

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Profile

Shozo MATSUMURA
Affiliated Fellow, NISTEP

Senior Expert Researcher, National Institute for Earth Science and Disaster Prevention. Dr. Matsumura specializes in seismology. His aim is to detect precursory phenomena preceding major earthquakes by observing microearthquakes. He is particularly interested in understanding the conditions of stress redistribution generated by slow slips and quasi-static slips from changes in patterns of seismic activity, with a focus on Tokai earthquakes. He is an Expert Member of the Headquarters for Earthquake Research Promotion.

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