

Development of Earthquake Prediction Research – Toward Practical Application (Official Earthquake Prediction Warning)

Toru Nakagawa (Professor Emeritus, Osaka Gakuin University)

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Abstract

Research on Earthquake Prediction has long been groping in the dark, but we now see light emerging in these 2 years. Tsutsui observed the electric field deep underground to capture its fluctuations immediately before and after an earthquake clearly, and Kamiyama et al. analyzed satellite data on crustal deformation over time to detect anomalous variations several years to several months before an earthquake.

Based on these clues, we discuss here ways to develop Earthquake Prediction Research to the practical application stage. In the practical application stage, public organizations will issue earthquake prediction notices (1 year to 1 month in advance), warnings (10 days to half a day in advance), and emergency warnings (2 hours to 10 minutes in advance) so that people and society can take measures to minimize earthquake damage. To achieve this goal, we will proceed in five stages, i.e., development/implementation of earthquake prediction methods (Stage 1), verification (Stage 2), large-scale deployment (Stage 3), establishment of technical systems (Stage 4), and public operation (Stage 5), while clarifying the tasks for each stage. We are just entering Stage 2, where several research groups jointly work to validate breakthrough methods. To manage such research projects, we should better establish a General Incorporated Foundation as the partner of EPSJ. In Stage 3, a project funded by KAKENHI (the Grant-in-Aid for Scientific Research) should play the main role, while in Stage 4, a national project will play the principal role. Assuming that 5 years are needed for each stage, it will take 20 years to achieve the final stage of public operation. We are determined to move forward with such a great vision and will.

1. Introduction: Purpose of This Paper

I have been working as a researcher all my life, first in physical chemistry, then in information science, and most recently in creative problem-solving methodology. I joined the Earthquake Prediction Society of Japan (EPSJ) in February 2015 and have been listening to scientific presentations all along with the feeling that earthquake prediction research is still in the dark. In December 2022, at the EPSJ conference, we came across Minoru Tsutsui's report on his observation of (a possible earthquake precursor) in the electric field deep underground. Inspired by this clear light, I made up my mind: "We have a clear clue on how to predict earthquakes and reduce the damage. I will support and promote the earthquake prediction research to help reduce earthquake disasters in Japan (and the world)" [1]. Then, at the EPSJ conference in December 2023, I

encountered two novel methods using satellite data by Makoto Kamiyama et al. and by Kosuke Heki, and became convinced that earthquake prediction research had moved beyond the stage of groping in the dark.

So I began to think, "In what direction and in what steps should we promote earthquake prediction research in the future?". The practical application of earthquake prediction (as opposed to probabilistic long-term/medium-term earthquake forecasting) is to observe some definitive earthquake precursor phenomena and issue notices/warnings shortly (several years to several days) before or immediately (several hours to several minutes) before the occurrence of an impending earthquake (based on the analyses of many similar cases in the past). For the notices/warnings to be effective, people and society must (be able to) react appropriately. If the notices/warnings are misleading (e.g., the predicted earthquake never happened, or happened at a completely different time or place), the burden on society would be so great that the earthquake prediction research would be seriously criticized. On the other hand, if a large earthquake occurs without warning, the damage to society will be much greater. Thus, in addition to the technical difficulty of prediction, earthquake prediction research bears a heavy responsibility for the reliability of prediction results. With this in mind, we will discuss the "Direction and Stages of Promoting Earthquake Prediction Research".

2. Vision of the Final Goal -- Public/Social Operation of Earthquake Prediction Notices/Warnings.

The ultimate goal of Earthquake Prediction Research is to reduce earthquake damage as much as possible by publicly/widely announcing notices/warnings of individual predicted earthquakes so that the people and society can quickly take measures for evacuation and protection. I believe that the following three levels of public announcements are appropriate.

Earthquake Prediction Notice: "Having observed the earthquake precursor event P1, it is predicted that an earthquake of magnitude Y1 is very likely to occur in area X1 at time T1. Relevant authorities in the area (such as government/local authorities, disaster prevention organizations, etc.) are advised to take precautionary measures. The public is asked to remain calm and to pay attention to future earthquake prediction warnings." The timing of this announcement is assumed to be one year to one month before the predicted earthquake, for the sake of certainty and timeliness of the prediction. (The information P1, Y1, T1, and X1 should be expressed carefully concerning their uncertainty/reliability).

Earthquake Prediction Warning: "Having observed the earthquake precursor event P2, it is predicted that an earthquake of magnitude Y2 is highly possible to occur in area X2 at time T2. All relevant authorities in the area (including government/local authorities, disaster prevention organizations, transport, hospitals, etc.) are requested to prepare immediately for their disaster prevention measures. All citizens in the area are advised to prepare for evacuation and disaster prevention in their vicinity. Please pay close attention to the possible "Earthquake Prediction Emergency Warning". The Emergency Warning may be issued only two hours to several minutes before an earthquake and any time of day or night". The timing of this warning announcement is assumed to be 10 days to half a day before the predicted earthquake.

Earthquake Prediction Emergency Warning: "Having observed the earthquake precursor event P3, it is predicted that an earthquake of magnitude Y3 has a very high risk of occurring in area X3 at time T3. All relevant authorities in the area (including government/local authorities, disaster prevention organizations, transport, hospitals, etc.) are urged to implement the measures immediately to reduce possible damage and causality. All citizens in the relevant area are also urged to take immediate evacuation and disaster prevention measures to ensure their safety. Whenever an earthquake occurs, an "Earthquake Early Warning" will be issued. Please pay close attention." The timing of this announcement is assumed to be 2 hours to several minutes before the predicted earthquake.

The issuance of Earthquake Prediction Notices/Warnings/Emergency Warnings has a great impact on society as a whole. Therefore, the issuing scheme must be publicly discussed and institutionalized in the Diet and other bodies. The people who will lead the discussion (and decide on the issuance of individual notices/warnings) will be the panel of experts (mainly the leaders of the Seismological Society of Japan (SSJ)). Therefore, the earthquake prediction methods must be understood well by the seismological community and academia in general.

Furthermore, the actual effectiveness of Earthquake Prediction depends on the (capability of) social organizations and the public to respond appropriately to the Earthquake Prediction Notices/Warnings. Therefore, the methods and capabilities of Earthquake Prediction need to be understood by the public through the media, disseminated to social organizations, and understood/approved by the national/local governments.

As a prerequisite for all of the above, we, the EPSJ, must have established reliable methods, technical systems, and a track record of verification of Earthquake Prediction. At the present stage, I evaluate that the Kamiyama method is promising for issuing Earthquake Prediction Notices and the Tsutsui method is promising for issuing Earthquake Prediction Emergency Warnings. However, I have not yet found any promising method for Earthquake Prediction Warnings (to be issued 10 days to half a day before an earthquake). We should also check whether our methods apply to different types (trench, inland, cluster, etc.) of damaging earthquakes (e.g., M 5.5 or greater). We should also learn about recent advances in seismology, especially in its observation and in the physics of the earthquake process.

3. Requirements for Earthquake Prediction Methods and the Status and Selection of Different Methods [1].

The fundamental requirement for Earthquake Prediction methods is to capture the "Earthquake Precursor Phenomena", that occur in conjunction with and shortly before the earthquake. However, this requirement can only be proven after extensive observation/analysis. Therefore, we will build prediction methods that satisfy the following **practical requirements** step by step.

- (1) Observable/measurable clearly with a high signal-to-noise ratio and rarely hidden by noise.
- (2) Observable similarly at several locations and earthquakes occur often as predicted.
- (3) Measurable in the automatic/stable/continuous manner and possible to predict where, when, and how large the earthquake will occur.

(4) Capable of predicting different types of earthquakes by integrating several methods. Useful to understand the process of earthquake occurrence.

(5) Reliable to operate the Earthquake Prediction Notice/Warning system.

These requirements correspond to the five Stages of Earthquake Prediction Research (as described below) and must be met step by step.

Figure 1 shows various methods currently under investigation, categorized by the **type of precursor phenomenon and measurement method**.

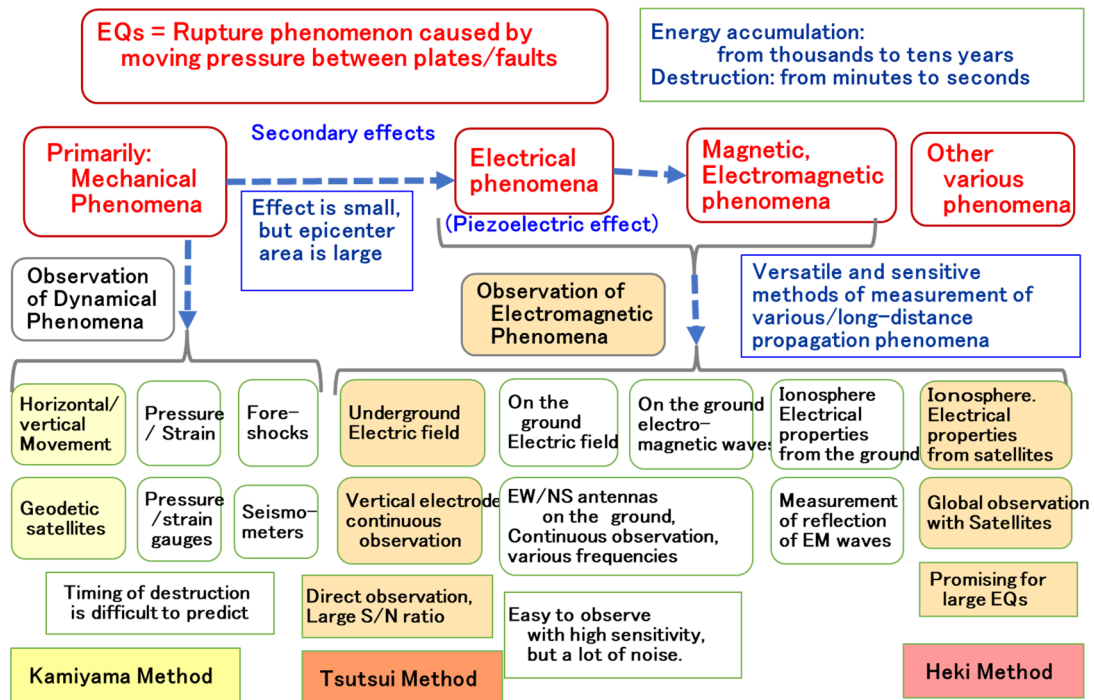


Figure 1. Different Earthquake Prediction methods: classification by precursor phenomena and observation methods [1] (partially edited)

The first category of candidate precursors is mechanical phenomena. Although various phenomena (such as crustal motion, subterranean strain, foreshocks, etc.) have been studied extensively, it has not been possible to estimate/predict the timing of earthquakes, i.e., destructive phenomena. Recently, using geodetic satellites, the crustal movement has been continuously measured and published with high precision, and Kamiyama et al. have developed a new method to analyze the data [3].

The second category is electromagnetic phenomena. Although they are secondary effects in earthquakes and several orders of magnitude smaller in terms of energy, they have great potential for new observation methods due to the huge size of the seismic region, the diversity of electromagnetic phenomena, and the diversity and high sensitivity of observation methods. Ground-based observation methods have been extensively studied, including observations of horizontal electric fields, electromagnetic waves, and remote sensing of electrical properties of the ionosphere. Such observation methods are versatile, sensitive, and simple. However, they are very difficult to obtain clear signals with a high S/N ratio due to various noises caused by nature and human activities. On the other hand, by continuously measuring the vertical electric field deep underground, Tsutsui recently observed clear, noise-free signals from the epicenter region and

detected the precursor events immediately before earthquakes [2]. In addition, Heki developed a method for analyzing the electrical properties of the ionosphere measured with satellites and showed the observation results of abnormal variation immediately (about an hour) before large earthquakes [4].

Fig. 1 does not include various other phenomena at the exploratory stage (e.g., groundwater level changes, radon emission, luminous phenomena, abnormal animal behavior, etc.), because they are quite unlikely to meet the requirements (1) to (5) shown above.

4. Proposing Five Stages of Promoting Earthquake Prediction Research

I propose the following five stages of promoting Earthquake Prediction research and developing various Earthquake Prediction methods for their official application use.

Stage 0: Survey/Plan/Preparation Stage: The principal actor is an individual researcher. He/she sets the aims of the prediction research, considers and plans the target phenomenon, measurement method, equipment, noise elimination method, feasibility, etc., and prepares for them (after reviewing previous works).

Stage 1: Method Development/Implementation Stage: The principal actor is a research group. The research group develops/implements a prediction method at a single observation site and demonstrates that a characteristic phenomenon is (was) measured before the earthquakes for several cases.

Stage 2: Method Validation Stage: The principal actor is a multi-group research project. The research project implements the same (similar) observation method at several observation sites in parallel and obtains similar signals for each earthquake to confirm that they are not noise. The project will validate that the observation method captures a precursor phenomenon of (some types of) earthquakes for a large number of earthquake events.

Stage 3: Large-scale Deployment of a Method: The principal actor is a large-scale research project funded by KAKENHI (the Grant-in-Aid for Scientific Research). The KAKENHI project deploys the observation sites (and research groups) of the method widely in Japan and observes many cases of earthquake precursor phenomena in different regions. Based on the results, the project creates a method to estimate (in advance) the area, magnitude, and timing of the impending earthquakes. It will then verify when and what kind of earthquake prediction information can be issued, and confirm the features and application limitations of the method.

Stage 4: Establishment of a Technical System for Earthquake Prediction: The principal actor is a national project. The national project integrates multiple prediction methods and establishes a technical system for Earthquake Prediction that can appropriately issue (within the national project on the experimental basis) Earthquake Prediction Notices/Warnings/Emergency Warnings for various types of earthquakes. The project will apply the technical system (by simulation) to a large number of past and ongoing earthquakes to verify its reliability.

Stage 5: Public Operation of Earthquake Prediction Warnings: The principal actor is a public authority. The public agency always operates the Earthquake Prediction technical system. Whenever a damaging earthquake is predicted, it publicly issues an Earthquake Prediction

Notice/Warning/Emergency Warning on time to request/direct the public and the whole society to take measures to reduce earthquake damage. (See Section 2.)

Different methods will progress through these stages at their own pace. The leaders of such methods should steadily advance their research/development and present their concepts/results at each stage. They should also prepare for the next stage by reaching out to the public, the scientific community (especially SSJ), the media, society (including local governments and businesses), and the national government. Pioneering projects and their methods will lead the progress to the next stage, probably taking about five years at each stage.

5. Three Novel Methods: Their Stage 1 Results and Stage 2 Challenges

We now focus on the three novel methods that have already achieved their results at Stage 1 and are approaching Stage 2. We introduce them here, using their recent presentations at the EPSJ conferences held in December 2022 and December 2023, and discuss the challenges they will face at Stage 2. (We expect their new reports at this conference, in December 2024).

Kamiyama Method: Time variation of crustal motion using GNSS satellite data: Useful for short-term prediction [3] (Figure 2)

Kamiyama et al. use the GNSS satellite-observed data openly published by the Geospatial Information Authority of Japan (GSI). The GEONET data contain the real-time precise positions of more than 1,300 points across Japan and the archives of the whole data since 1996 are open to the public use. Kamiyama et al. use the triangular mesh for analysis. They report an example of the 2018 Hokkaido Iburi East earthquake, with the epicenter marked with ★ in Fig. 2(a)(b).

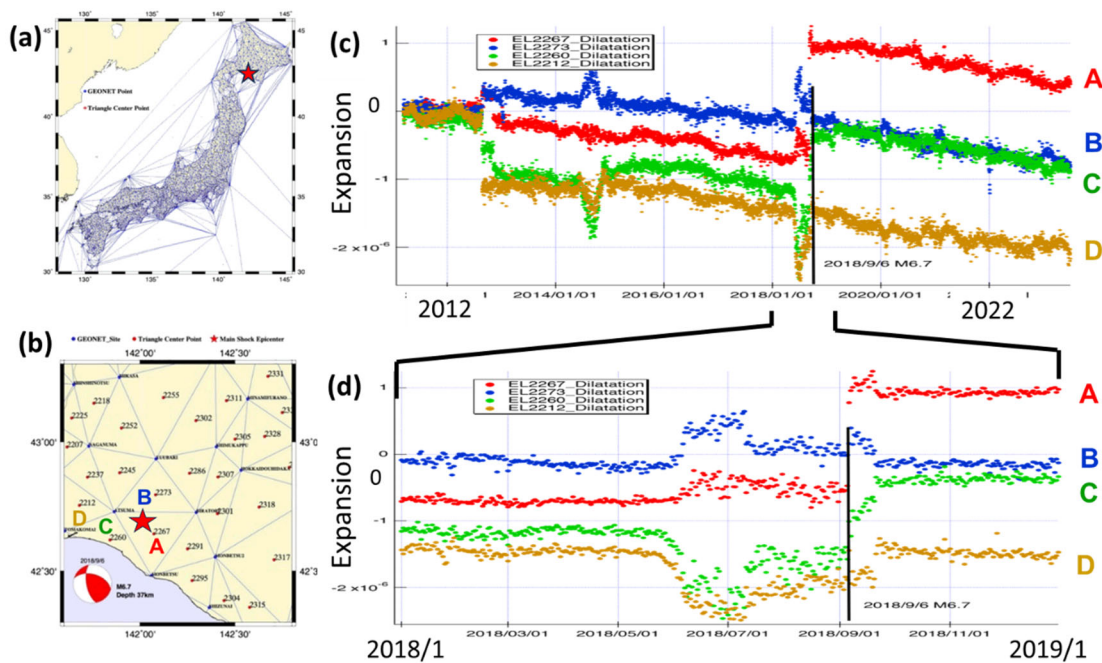


Figure 2. Kamiyama Method: Hokkaido Iburi East EQ (Sept. 6, 2018, M 6.5). [3] Edit configuration.

Historical variation of areas of four triangles around the epicenter is shown in Figs. 2(c)(d) using the indices normalized to be 1 at a common time. Fig. 2(c) plots the daily variation of such area

indices for the 12 years from 2011 to 2023, while Fig. 2(d) shows in more detail the year 2018. The four areas have been slowly shrinking for years, but on the 2018/9/6 earthquake (M_J 6.5), the areas of A and C suddenly expanded. In detail, all four triangles showed anomalous variations (with identical patterns disregarding the sign of shrinkage/expansion) from 3 months before the earthquake. Kamiyama et al. [3] reported three cases of earthquakes, where the anomalies appeared 3 years, 2.5 years, and 3 months before the earthquakes, respectively, showing different patterns of variation, such as gradual increase and stagnation after the increase.

-- Future Challenges:

- ▶ Perform similar analyses of all past damaging earthquakes in Japan and clarify the patterns of anomalous variation and their onset time.
- ▶ Develop a method of in-advance estimation of the region, magnitude, and timing of impending earthquakes.
- ▶ Develop software to produce similar plots of historical data for each region in summary (one point per month) and detail for anomalous periods.
- ▶ Patrol all regions of the country with the software to find the regions subject to possible Earthquake Prediction Notices.

Tsutsui Method: Observation of the DC electric field deep underground: Imminent Earthquake Prediction [2] (Figure 3)

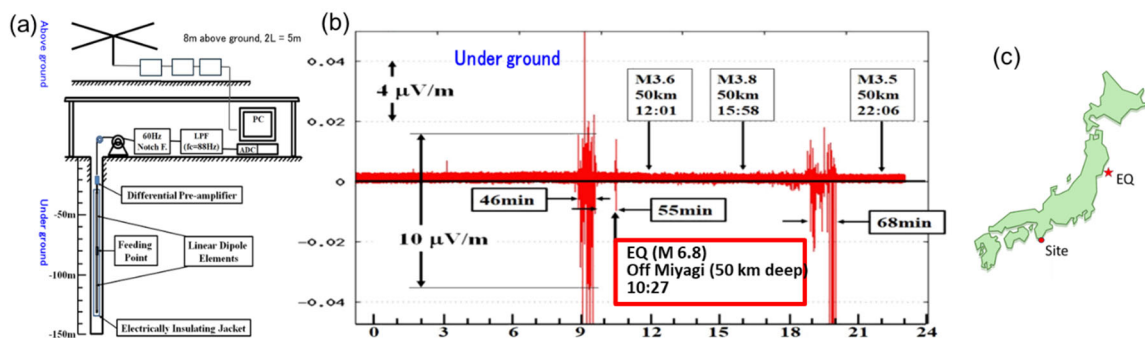


Figure 3. Tsutsui method: (a) instrument, (b) measured data on May 1, 2021, and (c) location of the epicenter [2].

Tsutsui built an observation site on an island at the southern tip of the Kii Peninsula and installed a 100 m long dipole-type DC electric field sensor in a 150 m deep borehole. The signals were measured continuously every second and stored in a PC. Figure (b) shows the data observed on 2021/5/1 for 24 hours. Steady noise was observed for nearly 9 hours, a violent (\pm) fluctuation occurred for 46 minutes, followed by 55 minutes of quiescence, then a pulse signal appeared at 10:27, followed by another 8 hours of quiescence, then a second violent (\pm) fluctuation occurred for 68 minutes, and back to quiescence. -- Since there was an M 6.8 earthquake off Miyagi (750 km away) at 10:27 the day, it was concluded that the signals were seismic in origin. This observation is groundbreaking indeed in many respects, such as clear and high S/N ratio, continuous measurement with a time resolution of 1 second, vivid and rich fine structure, etc. Professor Emeritus Tsutsui is now working alone on his private funding. Stage 2 verification of this method is urgently needed.

Future Challenges:

- ▶ Inherit Tsutsui's technology and know-how quickly and establish second, third, etc. research groups/observation sites.
- ▶ Resolve technical/financial difficulties related to site selection, borehole construction, equipment maintenance, etc. Obtain some funding for a substantial research project.
- ▶ Observe and record as many actual earthquakes as possible and accumulate the patterns of signals (especially the timing of the onset of precursors).
- ▶ Understand the fine structures of the signals (e.g., separation of the DC and ULF bands, and their relationship to the seismic process). Such understanding is both necessary and useful.
- ▶ Develop a method of in-advance estimation of the region/magnitude/time of the predicted earthquakes. Note that the transmission speed of the DC electric field in the bedrock is about half the speed of light and hence the usual method of estimating the epicenter location from the difference in arrival time of P-waves at multiple locations is not applicable. If the epicenter is uncertain, the magnitude is also uncertain. Some additional observation data/instrumentation is required.

Heki Method: Observing the variation of the total electron content in the ionosphere with GNSS satellites: Imminent earthquake prediction [4] (Figure 4)

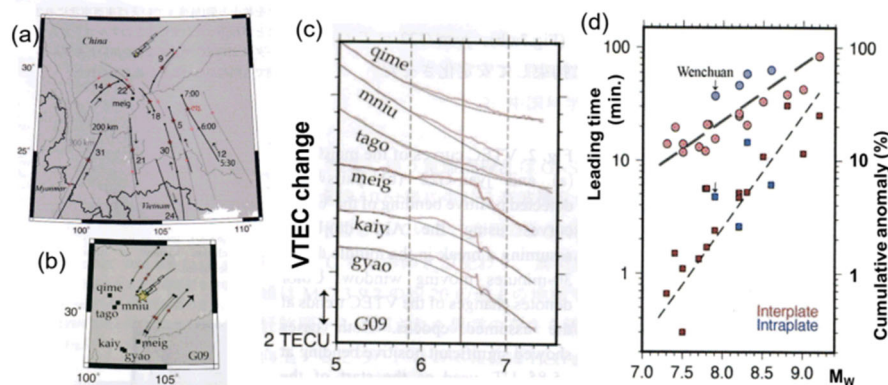


Figure 4. Heki method: (a) (b) (c) 2008 Wenchuan earthquake (M_w 7.8), and (d) summary of results for 20 cases [4].

Many orbiting GNSS satellites can measure the total electron content (TEC) on a straight line to ground stations. Assuming that all the TEC of ionosphere is located at an altitude of 200 km, we can project it to the ground. Figure 4(a) shows the epicenter location and the (200 km altitude equivalent) orbits of the many satellites in orbit at the time; satellite G09 is selected to be most suitable in this case. Figure (b) shows the (200 km altitude equivalent) orbits of satellite G09 as seen from several ground stations in the vicinity and projected on the ground. Figure (c) shows the time evolution of the TEC observed at these ground stations. The TEC normally varies on a quadratic curve, but in the case of large earthquakes, the TEC increases by several (to a few tens) percent for a short period. In the present case, the TEC data between G09 and ground station 'mei varied from 35 minutes before the earthquake with an increase of about 5%. Heki performed similar analyses for about 20 large earthquakes since (before) 2011 and summarizes the results in

Fig. (d). The lead time of the TEC variation before the earthquakes (upper graph) and the percentage of anomalous TEC increase (lower graph) are plotted against the magnitude of the earthquake.

Future Challenges:

- ▶ For practical applications, we need to define a region to monitor for possible earthquakes and observe the variation of TEC data continuously for all combinations of many orbiting GNSS satellites and several ground stations in the region. We need to detect if any graph of TEC varies from its regular quadratic curve, and then quickly decide whether such anomalous variation occurs in many other graphs as signs of possible earthquakes.

- ▶ This method may be useful to monitor and predict large earthquakes (M7 or greater) worldwide.

- ▶ However, the percentage of increase in TEC is small and has a risk of being confused by other natural events (e.g., geomagnetic activity, solar flares, etc.).

6. Proposal for Enhancing the Research System of the EPSJ

To promote the above research developments, we should discuss how to enhance the research system of our Earthquake Prediction Society of Japan (EPSJ). I propose as follows.

Strengthen the Basis of Research Collaboration and EPSJ Activities:

Firstly, I propose to make two lists of all the members of our EPSJ. List A, containing full details of individual members, will be used and kept in-house by the EPSJ office. List B will be posted on the members-only page of the EPSJ website and will contain members' details in a way partially hidden by the member's choice to protect their privacy. Second, in addition to the annual EPSJ conference, we will hold three informal meetings a year with presentations and discussions in hybrid face-to-face and online. Thirdly, we will introduce the Zoom software and use it for official meetings and informal discussion meetings among members. These measures will promote communication and cooperation among members and enhance the EPSJ activities.

Establish the "EPSJ Research Foundation" (provisional name):

I propose to establish a General Incorporated Foundation for legally managing and promoting the Stage 2 research project described in section 4.2. It is an offshoot partner of EPSJ, i.e., the (General Incorporated Association) Earthquake Prediction Society of Japan.

To carry out the multi-group research project at Stage 2, we need a research budget of tens of millions of yen (e.g., setting up an observation site for Tsutsui method may cost 10-20 million yen). Since it is practically impossible to get a research fund from KAKENHI for the time being, we EPSJ should better take the initiative to raise and manage funds for ourselves and encourage university laboratories and other organizations to participate in the joint project. I propose that EPSJ proactively establish the EPSJ Research Foundation, with EPSJ leaders serving as its directors/councilors and a qualified external person invited to manage the foundation.

My vision of the collaborative relationship between EPSJ and its Research Foundation is illustrated in Fig. 5 [5].

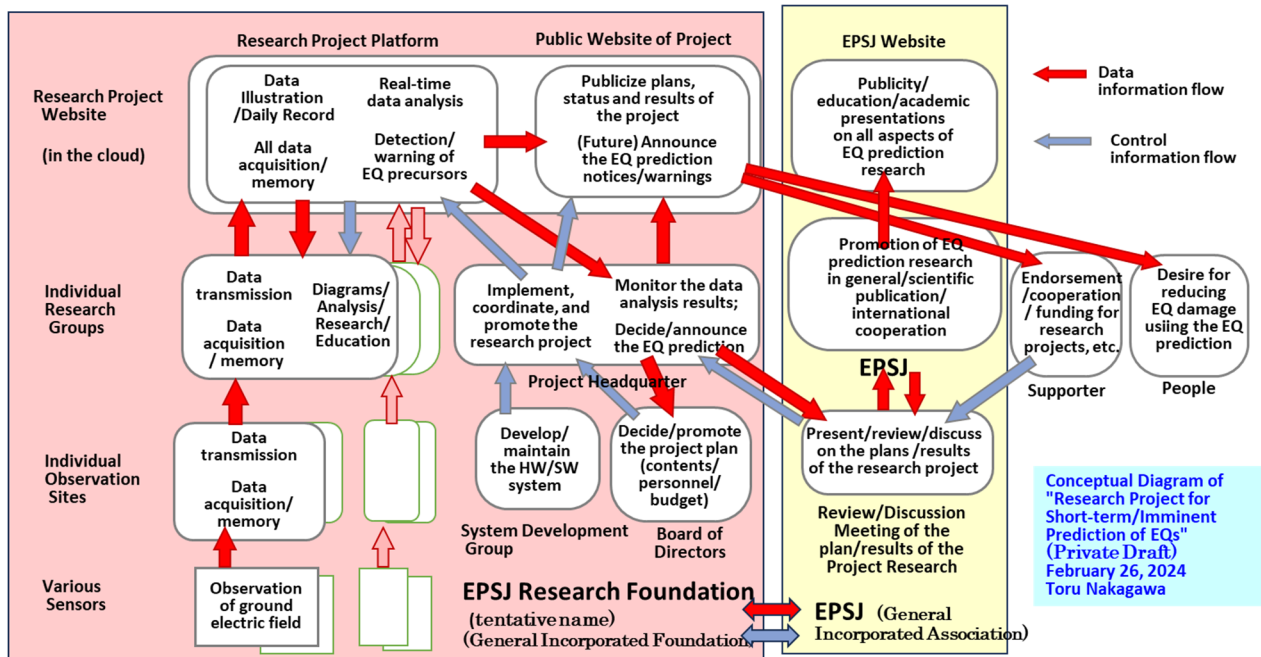


Figure 5: Proposal for project management by EPSJ and EPSJ Research Foundation (personal draft) [5].

The EPSJ Research Foundation is responsible for managing the research project, and the EPSJ is deeply involved in planning the research contents and evaluating the results. The figure shows the relationships among the project headquarters, the individual research groups, the EPSJ, and the society, particularly with the flow of research data and control information (using the case of the Tsutsui method). It also mentions the necessity of setting up the hardware and software system.

Present our results more to the academic community

We, the EPSJ and its members, should present our research results more widely to the academic community and society. This is the basis for promoting our research. We should always prepare to promote our research projects and obtain the KAKENHI budget at Stage 3. We should also make our EPSJ website more active.

7. Concluding Remarks

At the stage of our ultimate goal of Earthquake Prediction Research, a national agency issues Earthquake Prediction Notices/Warnings/Emergency Warnings, and the public and the whole society respond to them to take appropriate measures to reduce earthquake damage and causality. To realize such a situation, we must establish a reliable technical system for Earthquake Prediction in advance. To realize it, ... I continued to think this way further and found the general idea of the five stages of development of Earthquake Prediction research. I showed the tasks we should accomplish at the five stages, and the principal actors of the stages should be different,

step-by-step higher organization with wider scope and heavier responsibility.

The three methods (developed by Kamiyama et al., Tsutsui, and Heki, respectively) are introduced because they have completed Stage 1 (method development and implementation). They should proceed to Stage 2 (method validation), where the principal actor should be a collaborative project of several research teams. I propose to establish a new EPSJ Research Foundation as the offshoot partner of EPSJ to manage the project.

As for the current technologies expected to be used, the Kamiyama method is promising for short-term Earthquake Prediction Notices, and the Tsutsui method for immediate Earthquake Prediction Emergency Warnings. However, we find no promising method yet for Earthquake Prediction Warnings to be issued 10 days to half a day before a damaging earthquake. This is a big challenge for us in the Earthquake Prediction research.

We estimate that it will take about 5 years at each stage (2 to 5), and thus a total of 20 years for us to achieve the final goal at Stage 5, even in the case of smooth progress. We are very anxious about whether our nation can establish Earthquake Prediction measures to reduce huge earthquake damage before the impending Great Nankai Trough Earthquake.

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