Seismology Toward Research Innovation with
Data of Earthquake (STAR-E Project) promoted by MEXT

SYNTHA-Seis

NEWSLETTER

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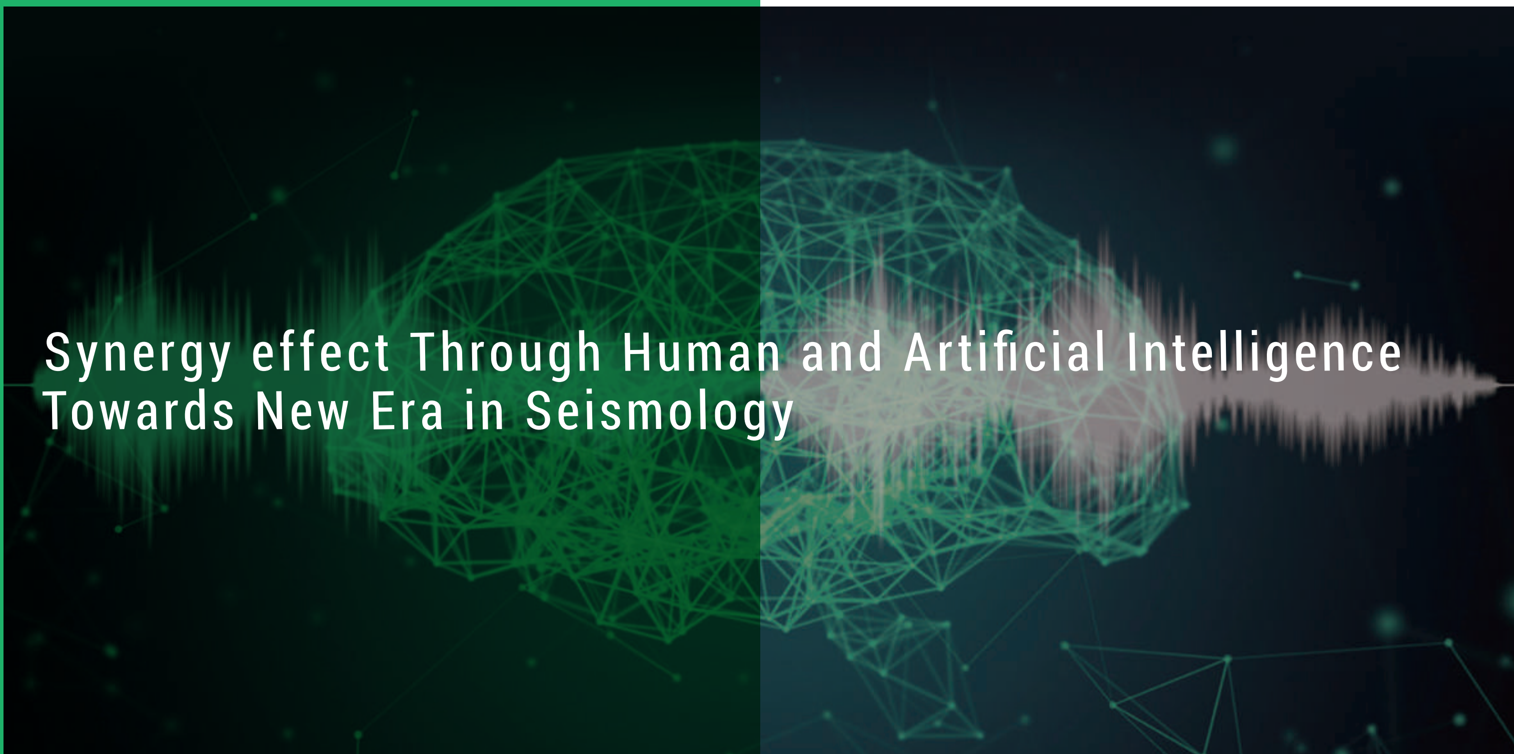
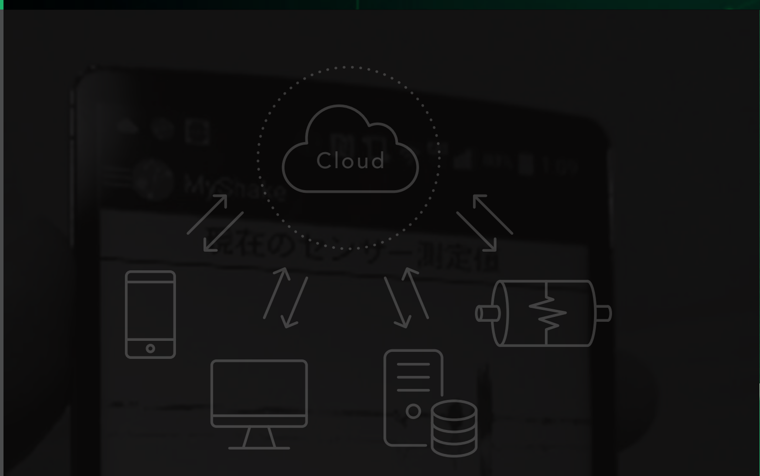
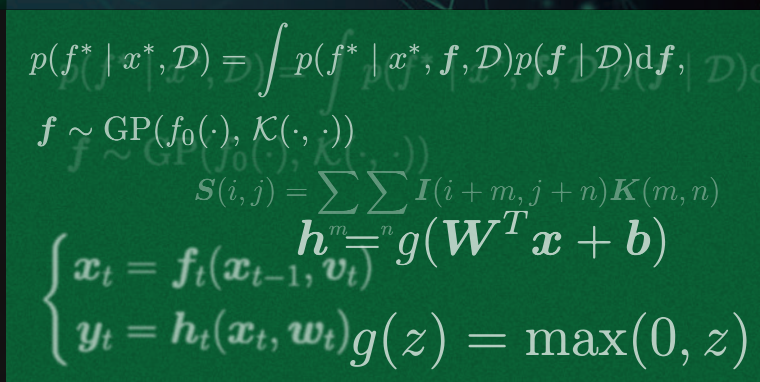


Synergy effect Through Human and Artificial Intelligence Towards New Era in Seismology





Roundtable Discussion: UTokyo Gr. x OsakaU Gr.

It All Starts with "Dialogue": The New Wave of Interdisciplinary Research

Seismology has been deepened by the human eyes and brains. Cutting-edge information science begins to accelerate its evolution.

SYNTHA-Seis, which started its research in July 2021, aims to breathe new life into earthquake research by organically harmonizing cutting-edge information science technology and conventional experience and knowledge in seismology under the theme of "dialogue and collaboration between artificial intelligence and human intelligence". I would like to take this opportunity to thank everyone involved in the MEXT STAR-E project for giving me this precious opportunity. Two years have passed since the start of this project, and through the collaboration of researchers in information science and seismology, we have developed a number of data analysis methods that contribute to earthquake research, including methods for detecting seismic waves from waveform signal data based on deep learning, low-frequency tremors from waveform image data, seismic activity estimation based on machine learning, and state estimation at seismogenic zone based on data assimilation. A number of data analysis and modeling methods have already been developed for earthquake research. Please look forward to SYNTHA-Seis' activities to deepen the interdisciplinary field of "Information Science x Seismology".

Principal Investigator: **Hiromichi Nagao**
Associate Professor, Earthquake Research Institute, The University of Tokyo

Earned Dr. in Science at Department of Earth and Planetary Science, Graduate School of Science, Kyoto University in 2002. After experienced a visiting researcher at the Japan Atomic Energy Agency, a researcher at the Japan Agency for Marine-Earth Science and Technology, and an associate professor at the Institute of Statistical Mathematics, he has been at the current position since 2013. He specializes in the interdisciplinary research between applied mathematics, statistics, and solid earth science.

STAR-E Project Manager: **Genshiro Kitagawa**
Professor Emeritus, The Institute of Statistical Mathematics
/The Graduate University for Advanced Studies

Human society is now facing a historic turning point due to the development of data science and AI, and the field of data science in Japan is facing an urgent need for human resource development. I have great expectations for the research itself that crosses AI and human wisdom, and at the same time, I believe it is equally important to nurture people in the process, and I hope that SYNTHA-Seis will do its best in both areas.

STAR-E Project Officer: **Naoshi Hirata**
Professor Emeritus, The University of Tokyo

In addition to slow earthquakes, there must still be other unknown phenomena that originate in the Earth's interior. It is an extraordinary challenge to find such phenomena from seismic observation data that can only be obtained once, unlike experimental data that can be reproduced. However, I expect that the researchers will combine their long-accumulated knowledge with cutting-edge artificial intelligence to develop the most suitable analysis method for seismology.

Human Intelligence Group Leader: **Kazushige Obara**
Professor, Earthquake Research Institute, The University of Tokyo

The field of solid Earth sciences, including seismology, has been in a critical situation in recent years with a gradual decrease in the number of young researchers. In such a situation, it is highly significant to have a dialogue with information science, a research field that is currently undergoing explosive development. I hope that this will encourage young researchers to enter the field, and that seismological research, which aims to accurately understand signals from the Earth's interior, will further evolve with the incorporation of new senses.

Artificial Intelligence Group Leader: **Koji Hukushima**
Professor, Department of Frontier Sciences,
Graduate School of Arts and Sciences, The University of Tokyo

I feel a strong enthusiasm to use whatever means we can now take to understand earthquakes. It is a well-known fact that data science is one of the most promising means of doing so, at that time, I myself have high expectations and interest in what data science can show us about the earthquakes and the Earth's landscape. I would like to bring out "new discoveries" as much as possible through the dialogue between data science and human knowledge.

Roundtable Discussion: UTokyo Gr. x OsakaU Gr.

It All Starts with "Dialogue": The New Wave of Interdisciplinary Research

Shin-ichi Ito
Assistant Professor, Earthquake Research Institute, The University of Tokyo

Masaaki Imaizumi
Associate Professor, Institute for Advanced Study, Graduate School of Arts and Sciences, The University of Tokyo

Kosuke Morikawa
Associate Professor, Graduate School of Engineering Science, Osaka University

Yoshikazu Terada
Associate Professor, Graduate School of Engineering Science, Osaka University

Under the project theme titled "Dialogue and Collaboration between Artificial Intelligence and Human Intelligence," leading researchers in the fields of artificial intelligence/machine learning, statistics, and earthquakes were brought together. With different interests and different backgrounds, they naturally have different ways of looking at things and different ways of thinking. What attracted them to participate in this project? First, we asked them to become aware of their differences and similarities through "dialogue".

A team of professionals with a wealth of expertise and experience

— What was the reason or impetus for your participation in the project?

Ito: When I was first told that the project was going to be about "dialogue between seismology and information science," I frankly thought it sounded interesting and decided to participate immediately.

Imaizumi: The main reason was that I was attracted by the personality and enthusiasm of Dr. Nagao. Of course, I have also long been interested in Dr. Nagao and his colleague's active research on the boundary area between seismic and data analysis.

Morikawa: My post-doctoral position was at Earthquake Research Institute (hereinafter called "ERI") , and the research I engaged at that time was very interesting. I would have loved to participate in this project because I can do further research with researchers in various fields.

Terada: When I was engaged in the research that Dr. Nagao, Dr. Ito, and Dr. Morikawa were working on, I was fascinated by their research on earthquake observation data...in fact, that was the first time I had ever worked with actual observation data properly. I was very attracted to the study of statistical seismology. That is how I came to study statistical seismology, and that is how I came to participate in this project as well.

Ito: Now, Dr. Terada, you mentioned that you handled observation data for the first time when you were engaged in project at ERI. How major is earthquake data in the fields of

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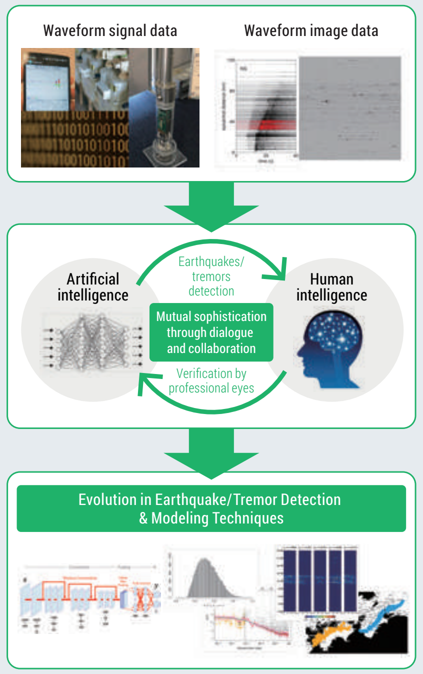
Synergy effect Through Human and Artificial Intelligence



statistics and artificial intelligence?
Imaizumi: Earthquakes are a fairly regional type of data, such as Japan and the West Coast of the U.S., so I don't think we see this type of data very often in the field of artificial intelligence.
Morikawa: I had only seen S and P waves as "examples" before I started working with them at ERI. I had almost no experience in analysis.
Ito: I see. So when it comes to method development, you usually use benchmark data.
Terada: You are right. However, once I started working with earthquake observation data, I found that not only does it have an expanse of time and space, but it also has ancillary information such as magnitude, which, to be honest, is very interesting. At the moment, there are still many difficulties even in modeling, but I am facing them with the desire to somehow create a new method or a method specialized for earthquake analysis.

—What is your role in this project?

Ito: I have always specialized in physics and have always been interested in complex phenomena such as destructive phenomena that cause things to break. Even now, my personal interest in knowing what is happening in earthquakes is a major motivating factor. In my role in the project, I hope to utilize my knowledge of physics as a bridge between seismology and information science.
Imaizumi: Since I specialize in the theoretical aspects of statistics and machine learning, I would like to successfully apply my knowledge of data analysis and data utilization to the area of earthquakes. I have great expectations that the interaction between experts in the real phenomena of earthquakes and experts in data analysis will lead to new discoveries.
Terada: I am also a specialist in statistics and machine learning, but I think I have also been focusing on applied research, so I would like to combine theoretical and applied perspectives in my mind first, and while actually working with my hands, I would like to develop new methods and engage in research that will provide knowledge that will help solve problems in the earthquake field.
Morikawa: My specialty is statistics, but I am not well versed in the use of artificial intelligence, so in this segregation, I plan to conduct my research on the natural intelligence side. Specifically, I would like to work on research that would elucidate the details of slow-slip phenomena, which have been attracting increasing attention in recent years. However, I am not an expert in seismology, so I would like to start by enjoying my research and meeting researchers in other fields.

Shin-ichi Ito

Specialty: Statistical physics, computational physics, and data assimilation. Recently, he has been working mainly on the advancement of data assimilation by random selection and its application to destructive phenomena in deep learning.

Challenging but essential theme for the development of earthquake research

— What was your impression when you first learned of the project theme?

Terada: At first I found it a very challenging task. It would be wonderful if we could collaborate well, but there would be many difficulties. For example, no matter how much data is available, simply handing data to someone and telling them to analyze it using machine learning is not going to result in meaningful research that will generate something new. However, it is presumptuous of me to say this, but the members gathered here this time have a wealth of knowledge and experience in both earthquake and information science, and considering the situation where we can proceed with analysis based on their own research know-how and advice from their own expertise, I have higher expectations for the project. Also, in terms of dialogue, statistics and artificial intelligence, which are also information sciences, may seem similar, but they are different in many ways, so I think that by successfully crossing them, we can create new value, such as establishing highly interpretable methods and models.
Imaizumi: My initial impression is that it always comes down to an important point. Artificial intelligence is gaining momentum in the world, and there is a tendency to think that anything is possible with artificial intelligence in all areas that deal with data, but in reality, there are many things that artificial intelligence is not good at, such as understanding things and finding phenomena that are often overlooked. And, as is the case with the discovery of

Masaaki Imaizumi

Specialty: Mathematical statistics and machine learning. Recently, he has been studying the approximation ability of deep neural networks and the stochastic behavior of large-degree-of-freedom models in relation to deep learning and high-dimensional statistics.

the slow-slip phenomenon, the knowledge accumulated on the natural intelligence side is very valuable, but until now, there has been little progress in reconciling the two. In such a situation, this project has brought together people who are able to maximize their respective expertise and who have a thorough understanding of different fields.
Ito: I think I am someone who was educated on the natural intelligence side, and I find it very interesting that the know-how accumulated in the physics world, which is obvious to me, has the potential to become completely new knowledge from the viewpoint of the information science world. To tell the truth, however, when I first saw the text, I did not understand what the term "natural intelligence" meant....
Morikawa: Indeed. What is natural intelligence? I know it is very new.
Ito: It means science that has been created by humans. Humans think, "This is probably what it looks like....
Imaizumi: However, from a relative standpoint, can't statistics also be seen as "leaning" toward artificial intelligence? What it does is quite mechanical. My idea of human intelligence is a bit more like "grandma's wisdom".
Terada: Isn't it also like when a person looks at something for a long time and notices a slight anomaly, etc.? I guess you could say it's like a deduction derived from comprehensive knowledge.
Imaizumi: It's something like, "If you see a sunset, the next day will be sunny."
Terada: Yes, that is exactly how I imagine it.
Imaizumi: From the standpoint of a researcher of artificial intelligence, I think it is an interesting topic to consider what it means for natural intelligence to understand things in the first place. In the world of physics, which is your specialty, if a law can be created, does that mean that it is understood?
Ito: Yes, I agree. When there is an unknown phenomenon and a theory that can properly explain it... I think it is more correct to say that I am happy than to understand it.
Imaizumi: Interesting, I would be happy to have an equation like F=ma. And that it is also a human intelligence understanding.... Recently, I have been thinking about this a lot in my research. There are many phenomena in the world that cannot be expressed as laws, but can be reproduced by artificial intelligence, even though they cannot be written down in an equation. To be precise, if it is something like "X multiplied by 1.68 times Y multiplied by 2.99," it can be written down as an equation. But can that really be called "understanding"? In other words, I am not sure that artificial intelligence understands, and this is also true for this project, but I wonder what exactly we have to accomplish to understand earthquakes.
Ito: As someone who has been educated on the natural intelligence side, I still want to know the "why" part. For all unfamiliar phenomena. But artificial intelligence is able to reproduce phenomena without understanding them well. Certainly, as we deepen our dialogue in the future, it will be important for us to be aware of the words and definitions in this area.
Imaizumi: At the risk of sounding a bit far-fetched, artificial intelligence is good at producing highly accurate forecasts. However, as an outcome of earthquake research, it is not necessarily enough to be able to predict. As Dr. Ito has said repeatedly, it is important to correctly understand what is happening, and if the original goal of earthquake research is to think about how to deal with earthquakes based on that understanding, then I believe that we need to rethink the meaning of the word "useful to society" that artificial intelligence researchers such as myself usually think of. I listened to what you all had to say today, thinking that we should start by getting rid of the "prediction is everything" scale.
Morikawa: I think you are right that what

Kosuke Morikawa

Specialty: Mathematical statistics, missing-value data analysis, and semiparametric inference. His recent research focuses mainly on point process data analysis, including statistical seismology and survival time analysis.

artificial intelligence researchers usually aim for and what earthquake researchers want to know are two different things. Since we are talking about a dialogue between artificial intelligence and human intelligence, I think it is necessary for us to have many dialogues and bridge the "gap" between the two.

Better from application to basic research than from basic research to application

— Once again, what are your expectations for interdisciplinary and multi-institutional joint research?

Ito: As I mentioned earlier, I think the most attractive thing about interdisciplinary fusion research is that what you think is not so novel can often be very novel from the viewpoint of other fields. I hope that new work will emerge from such insights, and conversely, I would like to provide some kind of hint that will lead to someone else's new research.
Imaizumi: In so-called data analysis projects such as this one, there are usually layers of basic and applied research, and the basic scheme is to utilize the technology cultivated by basic research in applied fields. In such a situation, what I am most interested in working on is the flow in the opposite direction. In other words, in the case of this project, I believe that the ideal way for cross-disciplinary fusion research would be for those of us on the basic research side to re-double our efforts to solve unsolved problems in earthquake research, and in the process, the quality of the basic research itself will be enhanced. I believe that this is the ideal form of cross-disciplinary fusion research. Of course, long dialogues among researchers are indispensable for this to happen, but I am very much looking forward to it.
Morikawa: The ETAS model (epidemic-type aftershock sequence model) in statistical seismology is just that kind of thing. And I think it is amazing because the ETAS model is not only the standard model for seismic activity, but it is now being used in economics research as well. It is exciting to think that a new statistical method like that could emerge from our dialogue.
Terada: Thinking about it, today was my first visit to ERI. It is a very valuable experience for me to know how the data I am going to analyze is actually obtained. I feel that this is another good thing about multi-institutional collaborative research.

— What is your outlook for the future or your respective enthusiasm?

Yoshikazu Terada

Specialty: Statistical science and machine learning with a focus on unsupervised learning. His recent research focuses mainly on the theory and applications of clustering methods and functional data analysis for large-scale data.

Terada: Our immediate goal is to build methods and models that those actually involved in earthquake research will consider necessary.
Ito: It would be great if we could combine the knowledge of seismology and informatics to discover unknown phenomena, and if we could achieve results that could lead to the prediction of earthquakes. I would also like to make an effort to disseminate useful information outside of the project, while being aware that cooperation between the two fields of informatics and seismology will continue to advance.
Imaizumi: Of course, it would be very valuable to achieve results that lead to disaster prevention and mitigation and to contribute to a significant reduction in human suffering (number of deaths)... however, since I am a theorist, I would like to learn more about earthquakes, deepen the public's understanding of them, and contribute to reducing the fear of earthquakes in the community, even if it's just a little less than now. This kind of thing is hard to visualize and hard to present clear goals. But I would be happy to achieve some results.
Morikawa: Since it is not easy for my research to be directly useful in some way, I would be happy if I could produce results that are useful to society and people in some tangible way. My ultimate goal is to lead to the detection of a huge earthquake in advance. It may take decades, perhaps even a century, to actually achieve this, but I hope that this project will somehow produce a foundation that will eventually lead to that goal.

— By the way, will the dialogue between artificial and human intelligence continue?

Ito: I don't think there is any conflict, and I think it will continue to deepen. It should not be the case that all the knowledge accumulated by people will be transferred to artificial intelligence and one day be eliminated....
Terada: If, through this project, there is more

that can be done with artificial intelligence, it means that the dialogue was successful, so now we can think of ways to incorporate the findings again, right?

Imaizumi: I totally agree with you. I believe that artificial intelligence will continue to absorb human wisdom, but we will be able to coexist well by "aufheben" and continue to do so for a long time to come.

Ito: And beyond the evolution of artificial intelligence, we may see the emergence of another new field of study in natural intelligence.

Terada: I think that is really how it is going to be. Let's make a team that can enhance each other.

A video of some of the roundtable discussions is also available on the SYNTHA-Seis website.

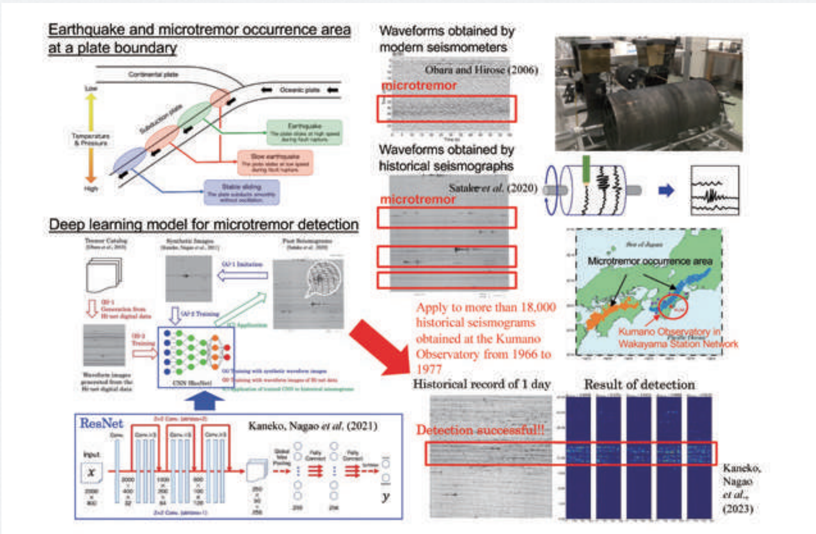
RESEARCH INTRODUCTION

01 Low-frequency tremor detection from historical seismograph records based on deep learning

Hiromichi Nagao
Associate Professor,
Earthquake Research Institute, The University of Tokyo

Slow earthquakes and low-frequency tremors, which were discovered about 20 years ago due to the enhancement of seismic observation networks, have been strongly inferred to relate to the occurrence of plate boundary-type great earthquakes, and have become one of the hot topics in current seismology. A list of tremor events recorded in modern seismic digital data for about 20 years (tremor catalog) has been constructed, but considering that the interval of large earthquakes is 100 to 200 years, it is clearly important in seismology to extend the time axis to the past and examine tremors contained in the data obtained by historical seismographs. Earthquake Research Institute, the University of Tokyo has a large amount of paper records of seismographs that were in operation about 50 years ago, and some of them contain waveforms that are thought to be tremors at that time.

In this study, we developed a convolutional neural network (CNN) to detect tremors from the paper records, using a residual learning model (ResNet). A single paper record contains a daily seismic waveforms recorded horizontally, but in this study, the images are divided vertically into five segments and input into ResNet, and the probability that each segmented image contains a tremor is calculated. Since tremors lasting more than several minutes are included in all five segmented images, even if a misjudgment occurs in some segmented images, it can be compensated for by judging the other segmented images. When the trained CNN was applied to historical recordings obtained at the Kumano Station of the Wakayama Observatory (Mie Prefecture) from 1966 to 1977, it succeeded in detecting many previously unknown tremors. It was also found that there existed periods of time when tremors were difficult to detect due to the unique characteristics of ancient recordings. In the future, we will use state-of-the-art GPU computers to train CNN with a larger amount of data in order to complete the catalog of tremors in the past.



Detection of deep low-frequency tremors from historical seismograph records based on deep learning

02 High-resolution uncertainty quantification for inhomogeneous frictional features in a slow-slipping fault based on large-scale data assimilation

Shin-ichi Ito
Assistant Professor,
Earthquake Research Institute, The University of Tokyo

Earthquakes occur when a fault slips, and the mode of motion depends on the spatial distribution of the frictional force generated in the fault plane. Therefore, investigating the details of the spatial distribution of frictional force is an important task for understanding the physics of complex fault movement. Since direct observation of fault deep underground is difficult, it is necessary to estimate "what the spatial distribution of frictional force should be to realize the observed motion" by using the limited observational data available and then, to estimate "where the major motion contributors are located" by quantifying the uncertainty involved in the spatial distribution. To achieve these goals, statistical methods such as data assimilation, which combines numerical simulation models of earthquakes and Bayesian statistics, have been used in recent years. However, earthquake models are generally large in scale, and existing data assimilation methods suffer from the "curse of dimensionality" easily, which makes these computations expensive and estimation difficult. Since this computational complexity limits the resolution of the spatial distribution to be estimated, there is a need to develop a new method to evaluate a detailed structure of the spatial distribution and its uncertainty.

This study developed a new data assimilation method based on the theory of numerical analysis and applied it to an earthquake model simulating a slow-slip zone off the Bungo Channel [Figure 1] to investigate the uncertainty of the spatial distribution of frictional force in the fault plane [Figure 2]. This method allows the detailed structure of the uncertainties to be evaluated with tractable computational complexity without limiting the resolution. The results of this study contribute not only to the physical understanding of seismic motion but also to practical problems, such as feedback to guidelines for efficient data acquisition based on comparisons between the structure of the detailed uncertainties to be estimated and the observed motions.

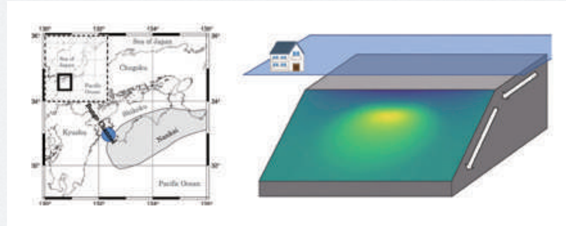


Figure 1: Earthquake model simulating the Bungo Channel slow-slip zone

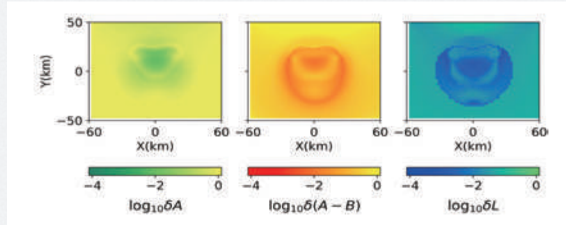


Figure 2: Spatial distributions of uncertainties in frictional features estimated by the proposed method

03 Fast and Precise Estimation of Temporal Variation of Aftershocks Immediately After a Main Shock Using Gaussian Process Regression

Kosuke Morikawa
Associate Professor,
Graduate School of Engineering Science, Osaka University

Immediately after a main shock, such as the Tohoku-Pacific Ocean Earthquake, a tremendous number of aftershocks occur due to heightened seismic activity. However, detecting aftershocks immediately after the main shock is challenging due to the contamination of arriving seismic waves. For instance, the earthquake catalog of the Japan Meteorological Agency clearly in Figure 1 shows the existence of under detected aftershocks after the 2004 Niigata-Chuetsu earthquake. Only aftershocks with relatively large magnitudes can be detected immediately after the main shock, while aftershocks with smaller magnitudes become detectable once the activity has subsided, typically a day later. Developing a method that can swiftly infer the characteristics of the original aftershock activity from such skewed data is a pressing issue. We have developed a method that corrects these biases by accurately modeling the aftershock detection probability. Specifically, we used Gaussian process regression, a machine learning technique, to yield precise estimates of aftershock detection probabilities, as shown in Figure 2.

Figure 2 illustrates the results of applying this proposed method to the seismic catalog of the 2004 Mid-Niigata Prefecture earthquake. The general trend is an increasing detection probability of aftershocks as time passes since the main shock. However, in some regions, there are violent fluctuations. These are believed to be caused by large aftershocks temporarily, making the detection of other aftershocks difficult. The proposed method enables detecting such abrupt changes.

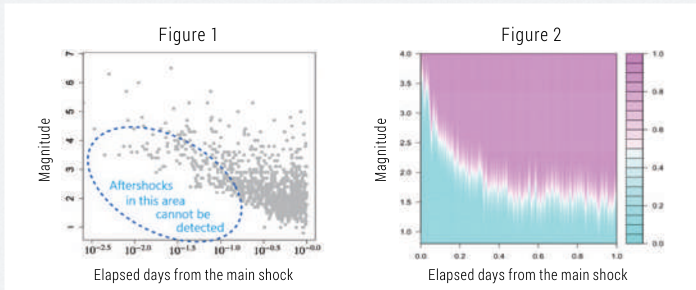


Figure 1: Aftershocks detected within one day immediately after the 2004 Niigata-Chuetsu earthquake (JMA catalog). The horizontal line indicates the elapsed time from the main shock (day), and the vertical line indicates the magnitude of the aftershock.

Figure 2: Predicted probability of aftershock detection probabilities obtained by applying this method to the 2004 Niigata-Chuetsu earthquake data.

MEMBER

The University of Tokyo Group	**Principal Investigator** **Hiromichi Nagao** Associate Professor, ERI, UTokyo **Co-Investigator** **Kazushige Obara** Professor, ERI, UTokyo **Aitaro Kato** Professor, ERI, UTokyo **Hiroshi Tsuruoka** Associate Professor, ERI, UTokyo **Shigeki Nakagawa** Associate Professor, ERI, UTokyo **Shin-ichi Ito** Assistant Professor, ERI, UTokyo **Tomoki Tokuda** Project Reseacher, ERI, UTokyo **Gerardo Manuel Mendo Pérez** Project Reseacher, ERI, UTokyo **Shinya Katoh** Project Reseacher, ERI, UTokyo **Koji Hukushima** Professor, Department of Frontier Sciences, Graduate School of Arts and Sciences, UTokyo **Masaaki Imaizumi** Associate Professor, Institute for Advanced Study, Graduate School of Arts and Sciences, UTokyo
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New Researcher

Tomoki Tokuda
Project Reseacher,
ERI, UTokyo

I specialize in machine learning methods, especially cluster methods. I am very happy to participate in STAR-E and hope to contribute to the discovery of a sparkling "STAR" in seismology through the magic power of AI.

ACTIVITY REPORT

Let's take a look at the lab in UTokyo [2022.3.28]

Discussions were held with high school students titled "Lecture on the Use of Artificial Intelligence Technology in Earthquake Research".

JpGU 2022 Session [2022.5.22]

We organized the session entitled "Seismic Big Data Analysis Based on the State-of-the-Art of Bayesian Statistics".

AOGS 2022 Session [2022.8.2]

We organized the session entitled "Data-driven Modeling in Geoscience".

Japanese Joint Statistical Meeting 2022 Session [2022.9.7]

We organized the session entitled "The forefront of earthquake big data analysis".

Seismological Society Japan Fall Meeting 2022 Session [2022.10.24-26]

We organized the session entitled "Deepening Seismic Data Analysis and Modeling with Bayesian Statistics".

Media Coverage

The Yomiuri Shimbun featured an article "Elucidating Earthquake Phenomena and Tackling Disaster Prevention".
The Sankei Shimbun featured an article "Slow earthquakes probed by AI Detecting" in their Close-up Science News.

Professor Kazushige Obara received the Medal with Purple Ribbon in the fall of 2022 [2022.11.3]

He was awarded the Medal with Purple Ribbon for his achievement in the creation of the "Science of Slow Earthquakes" based on the discovery and clarification of various slow earthquakes triggered by deep low-frequency tremors.

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