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Computing Crustal Deformation with Uncertainty Quantification

– Large-Scale Earthquake Simulation beyond Common Sense

“In an ideal simulation, I would like to do this calculation, but the number of calculations is huge, so it is impossible.” Overcoming problems like this is a showcase for simulation researchers. Prof. Ichimura, who studies earthquake simulation, has released many computational technologies that enable ideal calculations with existing computational resources. “Five or 10 years from now, when computational resources such as the supercomputer Fugaku become available to more people, we will be able to make improvements based on our achievements for their own purposes. We are pursuing methods that can be used with modifications that suit each purpose based on our results,” Prof. Ichimura said, introducing his research.

Tsuyoshi Ichimura
Professor/Head of Center, Research Center for Computational Earth Science, Earthquake Research Institute, The University of Tokyo

Large-Scale Earthquake Simulation – A Pressing Need for Society

To allow the government to decide how to prepare for future major earthquakes, such as a direct hit on the Tokyo Metropolitan Area or a Nankai Trough earthquake, more accurate earthquake assessments are required. It is not possible to predict when an earthquake will strike, but better assessments will enable disaster prevention professionals to make better measurements and decisions. To construct an integrated prediction system for quantitative assessments of earthquakes, in April 2020, one of the Programs for Promoting Research on the supercomputer Fugaku was launched. The name of the study is “Large-scale numerical simulation of earthquake generation, wave propagation and soil amplification" (Principal Investigator: Dr. Takane Hori, Japan Agency for Marine-Earth Science and Technology).

Prof. Ichimura is creating a series of innovative earthquake simulation methods in this program. Here we introduce two representative simulations from his results.

A Comprehensive Simulation from the Fault to the Structures, Which Has Been a Long-Standing Issue[*1]

In an earthquake simulation, researchers calculate how the waves generated at the fault propagate through the earth's crust and soil, until they meet structures such as buildings and houses and make them shake. However, to accurately simulate wave propagation, the crust and soil must be calculated on a fine grid. Furthermore, simulating the shaking of structures due to transmitted waves requires a huge number of calculations. That makes it difficult to analyze everything from the fault to the structures at the same time, targeting a wide area.

Fig. 1 A comprehensive simulation from the occurrence of an earthquake to the shaking of structures on the entire Kanto Plain

They simulated a model consisting of the crust and ground in an area including the Kanto Plain (256 km east-west x 205 km north-south x 100 km depth) and a highly concentrated city around a terminal train station. The size of the lattice ranges from about 0.125 to 64m, and the scale of calculation is 320 billion degrees of freedom. The calculated area consists of soft soil layers on heterogeneous crust, as well as above-ground and underground structures. The complex geometry of the structure is modeled in detail with a very fine mesh of minimum 0.125m.

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“Therefore, we usually divide the domain from the fault to the structure into several stages and perform calculations,” Prof. Ichimura says. “Is it possible to obtain correct calculation results with this method? Aren’t there any ways to calculate all of them at once continuously?”

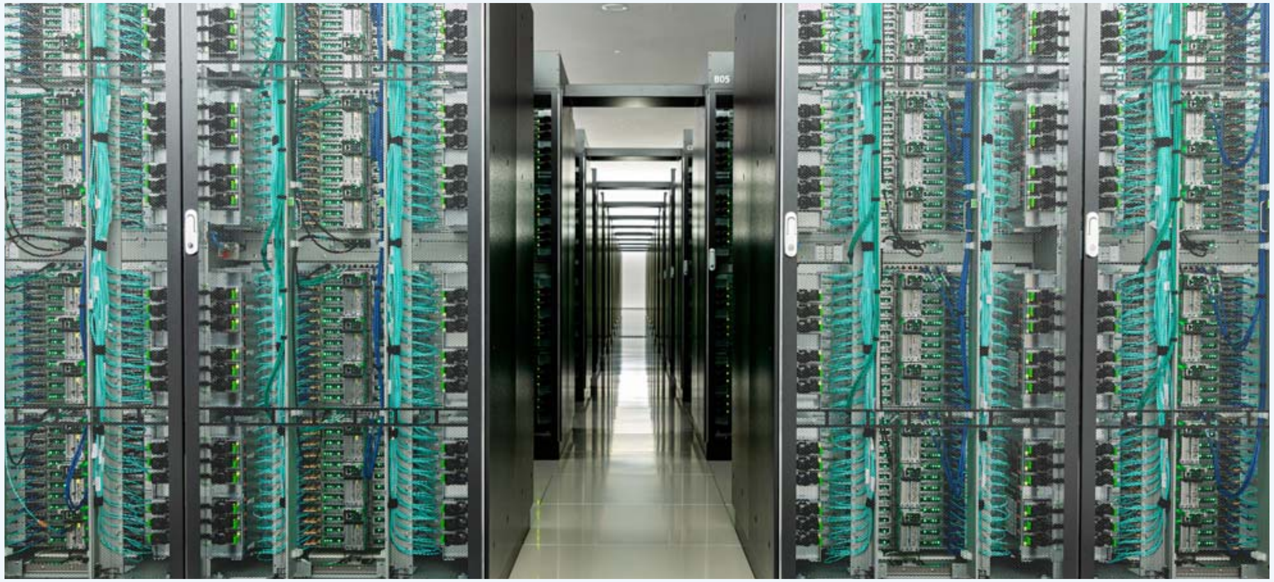
Using Fugaku, Prof. Ichimura and his colleagues took on the challenge and succeeded in conducting a comprehensive simulation from the fault to the structures, targeting an area including the Kanto Plain around Tokyo (Fig. 1). It took a lot of ingenuity to make full use of the characteristics of Fugaku as a computer suitable for the fusion of data science and simulation. Prof. Ichimura had previously developed a learning method[*2] using artificial intelligence (AI), and this time he developed this into a revolutionary data learning method. By accumulating the calculation results during the simulation and learning the data in real time, the initial value of the subsequent calculation called the iterative method can be estimated with high accuracy. This reduces the amount of computation and speeds up the simulation. As a result, he and his team achieved a calculation speed 1,070 times faster than the maximum performance of RIKEN’s K computer.

A Large-Scale Simulation with 32 Trillion Degrees of Freedom that Surprised the World[*3]

Prof. Ichimura and others also took up the challenge of simulating the Nankai Trough. This is a large-scale simulation of the ground surface deformation that occurs immediately after a large earthquake caused by the slip of the fault. The feature of this simulation is that it handles a wide area and includes “ambiguity.” Ordinarily, this is such a huge problem they would not even attempt it because the number of calculations required is enormous.

What do they mean by “ambiguity”? The hardness of the earth's crust is not actually directly measured by digging, so its hardness cannot be determined as a single value. It is more reliable to express it as “this kind of crustal deformation occurs with this probability” with a certain distribution.

When simulating uncertain events while considering probability like this, researchers usually use a method called the “Monte Carlo simulation.” This calculation method



repeatedly selects one numerical value from the possible range of values and perform calculations with it, but in order to obtain highly accurate results, it is necessary to repeat the calculation more than 10,000 times. Therefore, doing a wide-area earthquake simulation is beyond even Fugaku's abilities.

Instead, Prof. Ichimura and his team performed a simulation using a calculation method called the stochastic finite element method. With this method, results with distribution can be obtained in a single calculation. The calculated area covers the entire Japanese archipelago, which measures 2,496 km east-west, 2,496 km north-south, and 1,101 km deep, with a scale of approximately 32 trillion degrees of freedom. The finite element method, which is the basis of the stochastic finite element method, is thought to be unsuitable for large-scale calculation. Even 10 million degrees of freedom was considered large, and only a billion could be calculated at most. So, researchers around the world were amazed at the 32 trillion degrees of freedom of the stochastic finite element method. What's more, Prof. Ichimura's calculation is 224 times faster than the previous record. The reason the team could perform such large-scale calculations so quickly was that they studied a method to execute calculations using Fugaku skillfully from the aspect of computational science and computer science.

However, the code to perform this calculation contains thousands-lines complex parts that would be prone to errors if written manually. Therefore, Prof. Ichimura and his colleagues created software to have a computer automatically write a complicated part of the code.

This achievement of a large-scale, precise simulation that considers the "quantification of uncertainties" has attracted attention from all over the world. Regarding this calculation method, Prof. Ichimura said, "People who had given up on considering ambiguity in large-scale problems would wonder, 'Is there such a solution?' If we can obtain information on the slip of the fault, we can use this research to understand the deformation of the ground surface. The value of the deformation can be used as data for post-earthquake predictions. Since this method can handle hard objects, it can be used in applications other than earthquakes."

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Please see Figure 2 in the following paper.
"Extreme-scale earthquake simulation with uncertainty quantification," SC '22 Proceedings
https://dl.acm.org/conference/sc/proceedings

Fig. 2

Simulation of Nankai Trough earthquake considering ambiguity

The team simulated an area of 2,496 km x 2,496 km x 1,101 km centered on the Nankai Trough (which includes the entire Japanese archipelago). Maps in lower half represent the magnitude of deformation in the x, y, and z directions. Simulation results of "mean," "mean + 3σ (σ is the standard deviation; the probability of falling within this range is 99.7%)" and "standard deviation" are shown. This broad range of results enhances the quality of the simulation.

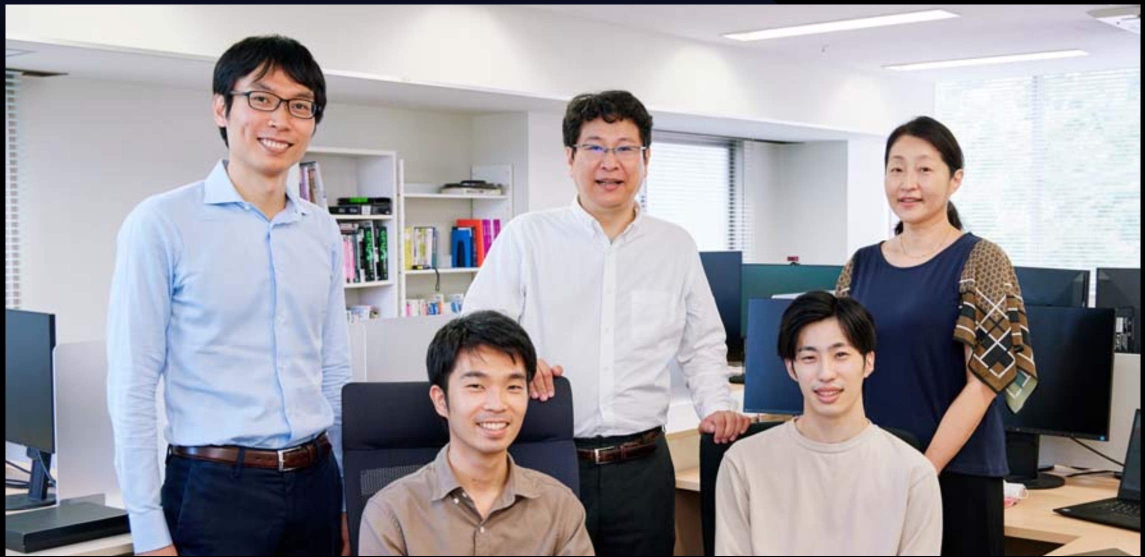
Prof. Ichimura continued, “In this simulation, we calculated the deformation immediately after the earthquake, but I would like to solve deformation over time and more complex nonlinear deformation.” He is excited at the prospect of tackling problems that are even more complex, with the computation amount increasing exponentially. He and his team will continue to create innovative methods to get closer to the “ideal simulation.” The team members have high hopes for the next move.

*1: HPC Asia 2022 Best Paper Award research results
*2: Workshop on Accelerator Programming Using Directives (WACCPD 2021) Honorable Mention award-winning research results
*3: 2022 ACM Gordon Bell Prize finalist research results

About the

Researcher

From novels to science texts, Prof. Ichimura as a child read books whenever he had free time. He liked to think, “What’s going to happen next?” When he entered the University of Tokyo, he chose to study science, but at the end of his sophomore year, he seriously considered going into the Faculty of Letters or the Faculty of Economics; he ended up choosing the path of Civil Engineering, where he could come into contact with a wide range of academic subjects. He began to devote himself to earthquake simulation research, which he started with his graduation thesis.



The members of the lab: from left in the back row, Associate Professor Kohei Fujita, Prof. Ichimura, and Project Academic Support Specialist Yumiko Nagasaki. From left in the front row, Ryota Kusakabe, a third-year doctoral student, and Souta Murakami, a second-year doctoral student.

Associated Research Projects

Large-scale numerical simulation of earthquake generation, wave propagation and soil amplification (hp200126/hp210171/hp220171)

Principal Investigator: Takane Hori, Japan Agency for Marine-Earth Science and Technology

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