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Review:

Fusion of Real-Time Disaster Simulation and Big Data Assimilation – Recent Progress

Shunichi Koshimura†

International Research Institute of Disaster Science, Tohoku University
Aoba 468-1, Aramaki, Aoba-ku, Sendai 980-0845, Japan
†Corresponding author, E-mail: koshimura@irides.tohoku.ac.jp
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This paper reports the latest outcomes of the project "Establishing the Advanced Disaster Reduction Management System by Fusion of Real-time Disaster Simulation and Big Data Assimilation" that started in 2014. The objectives of targeting various kinds of damage due to earthquakes and tsunami, fusion of large-scale high-resolution numerical simulation, effective processing and analysis of big data from various observations, and data assimilation were achieved. The outcomes will be utilized to create the world's first real-time simulation and big data analysis basis that would potentially assist with designing preliminary measures based on quantitative data and disaster responses to a disaster. Case studies using recent disasters were used in this endeavor and validation were performed. In the future, environments that rapidly provide information on possible damage situations in real time for public agencies, corporations, and citizens facing a catastrophic disaster in Japan will be developed by integrating these studies.

Keywords: real-time simulation, earthquake, tsunami, high-performance computing, GIS, big data

1. Introduction

Lessons for reducing damage by future disasters as obtained from the Great East Japan earthquake and the Nankai Trough earthquake include sharing of images of possible disaster sequences and impacts. The findings also emphasize enhancing resilience against disasters by taking specific measures to mitigate and prevent damage from spreading. In order to respond to this social demand, the authors launched a research project team to create a state-of-the-art technology for responding to disasters and proposing disaster reduction measures.

The research project establishes fusion of large-scale high-resolution numerical simulation and effective processing and analysis of big data from various observations as well as data assimilation to target various kinds of phenomenon and damage caused by earthquakes and tsunami. Using advanced simulation and sensing/observation tools, this study creates environments that rapidly provide information on possible damage situations and responses in real-time for public agencies, corporations, and citizens facing a catastrophic disaster in Japan.

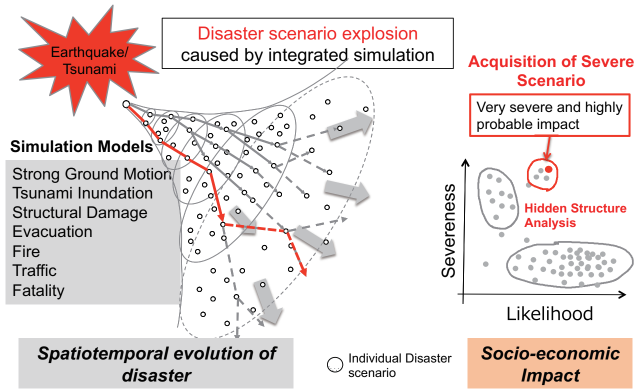

Fig. 1. Schematic explanation of the study from the perspective of theory and method development.

This paper reports an outline of recent research outcomes as an introduction to the special issue of the Journal of Disaster Research on "Disaster and Big Data 2," following the previous report [1]. Please refer to the main body for detailed outcomes of each research group. In particular, the Kumamoto earthquake that occurred in April 2016 was taken as an important case study to perform technological demonstrations in this research project.

2. Structure of the Research Project

The research scheme designed to achieve the goal is shown in **Fig. 1**.

In the overall scheme, the following three issues are addressed.

1 Design and integration of a simulation and damage prediction model using "observation big data." In addition to sensing data from high-density seismic network and other systems, information on location, fire, and collapsed buildings as obtained from mobile devices, as well as observation data from applications such as satellite and airborne imagery are collected and processed. By developing the theory

and method that can produce a model to respond to various circumstances based on the acquired data, advanced human response analysis and evacuation models are effectively realized. This is especially true for spatiotemporal evolution and the chain of damage phenomenon that occurs after a major earthquake and tsunami disaster.

2 Extraction of latent structure and finding important disaster scenarios based on enormous simulation results. A method is developed for analyzing and extracting the latent structure of the enormous disaster scenarios obtained by simulation. Important scenarios (severe disaster scenarios) can be formulated with minimized "unexpected" ones by controlling scenario explosions.

3 Construction of analysis basis using big data to reduce earthquake and tsunami impact. The methodology and technology to analyze the big data obtained after huge disasters is developed along with the method for formulating scenarios using latent structure analysis and acquiring high-order models. In addition, next-generation big data analysis basis for reducing earthquake and tsunami disaster is developed based on basic information processing technology such as simulation data warehouse and non-order database engine that make simulation fusion and high-speed processing for big data possible.

Each element technology is developed and integrated based on the above overall scheme. This paper reports the preliminary results from the elemental studies and case studies from recent disaster event.

3. Preliminary Outputs

3.1. Simulation and Sensing of Disaster Impact (Tohoku University)

A framework for real-time tsunami inundation and damage forecasting was constructed by integrating technology from three elements: simulation of tsunami propagation and inundation, estimation of building damage, and mapping.

It should be noted that this technology is considered different from "tsunami forecast and warning." Tsunami warning is issued by the Japan Meteorological Agency (JMA) in accordance with the Meteorological Service Act in Japan. The JMA predicts the height of the tsunami (m) for 66 forecast areas in Japan. The basis for forecasting is the tsunami model database compiled from more than 100,000 earthquake faults scenarios (prediction system driven by database). The main advantage is that the tsunami height is estimated within a few minutes of earthquake occurrence using the database of tsunami height and arrival time linked to earthquake information (epicenter location and magnitude). On the other hand, the JMA system does not forecast inundation. As is evident from the Great East Japan earthquake, tsunami penetrations on

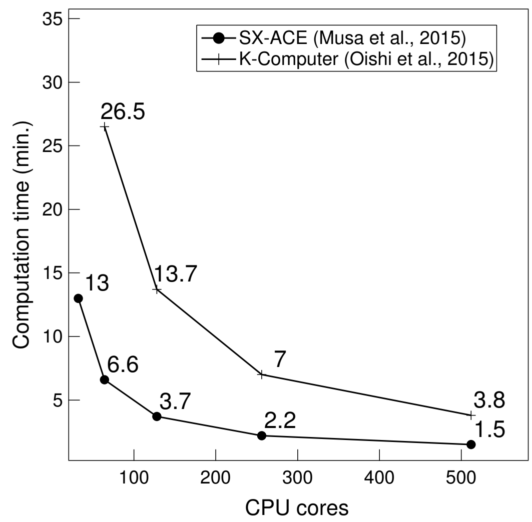

Fig. 2. Comparison between the performance of real-time tsunami inundation simulation system developed by the author's group [4] and using the K computer [3]. The vertical axis shows time required for two-hour inundation prediction, while the horizontal axis shows the number of CPU cores.

the land must be predicted rapidly and precisely to predict damage and initiate evacuation actions in response to the huge tsunami. We aim for rapid estimation of inundation areas and damage. Responses during the early disaster phase can be supported by disseminating estimated "tsunami height" and "inundation areas." Inundation areas can be estimated precisely by appropriately expressing land usage and building locations in the simulation model. In addition, more rapid and effective aid activities can be facilitated by quantitatively predicting damage information such as population, the number of exposed buildings, and the number of devastated buildings in the inundation areas.

Here, two challenges are presented. The first challenge is to determine tsunami generation. A fault model related to the fault rupture mechanism is required to set the initial conditions of tsunami numerical simulation. GNSS technology including GEONET has enabled new seismic and crustal observations, possibly increasing the accuracy of tsunami generation models (tsunami source models). On the other hand, it takes more than several hours for conventional workstations to complete inundation, making real-time simulation difficult. High Performance Computing Infrastructure (HPCI) can help solve this issue. For example, our research group has accelerated tsunami prediction computation by uniquely operating the vector-type super computer SX-ACE at the Cyber science center of Tohoku University as the "disaster mode," i.e., assign required computation resources after an earthquake occur. This ensures the performance of the super computer whenever an earthquake occurs. The specific goal of the present research is to determine tsunami generation model (source model) within 10 minutes and complete inundation simulation with a high resolution of 10-m grids within 10 minutes. We called this "10-10-10 (triple ten

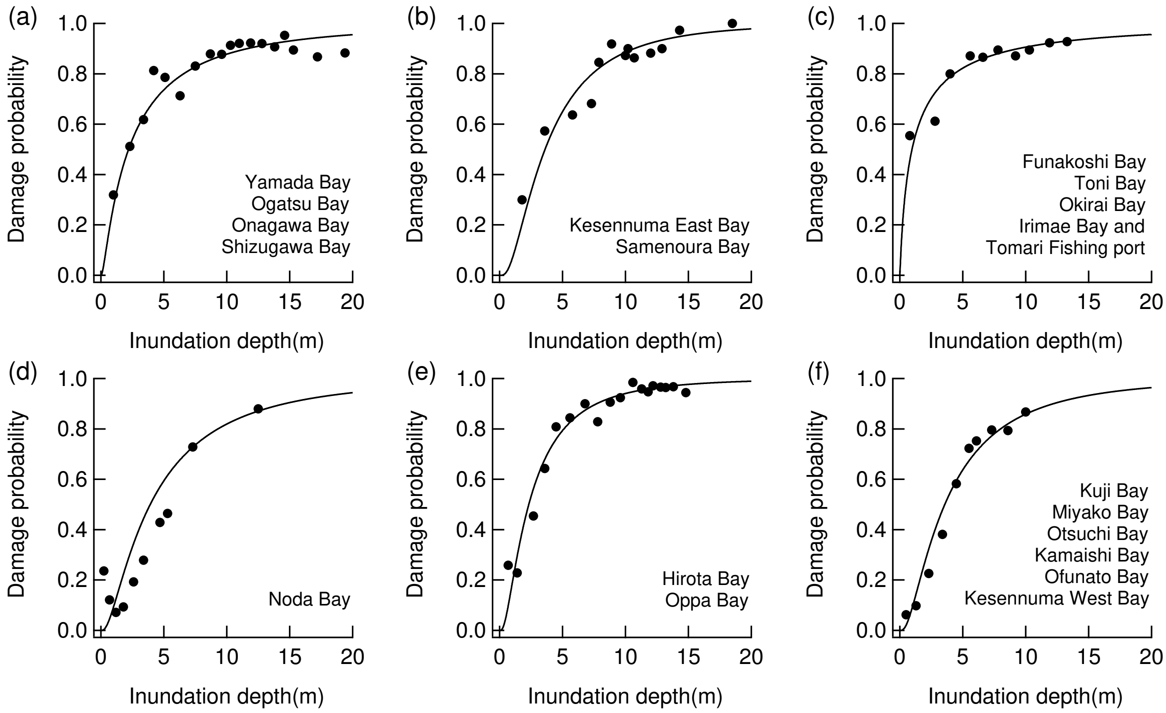

Fig. 3. Tsunami fragility functions categorized according to locality [5].

challenge)" in demonstration efforts and achieved the goal as described in [1, 2].

The computational performance of the proposed method was compared with that of the K computer [3]. The tsunami simulation codes used in this study was successfully optimized, and the SX-ACE showed overwhelming performance with the same number of cores (**Fig. 2**). As a result, high-precision inundation forecasting for one forecast district of the JMA (roughly corresponding to one prefecture) could be completed in three minutes 30 seconds using 256 cores. The results were reported in SG15, an important global conference on super computing, and well received [4].

The second challenge is damage estimation. For that, quantitative analysis about the tsunami inundation depths at which a wooden building or reinforced concrete building would collapse is required. It is possible to estimate building damage from inundation estimates results with 10-meter grids. On the other hand, the damage resulting from the Great East Japan earthquake showed that the tsunami external force and damage level differ from area to area. Our previous study analyzed all the tsunami damage data for the Iwate and Miyagi prefectures again and categorized the simulation results into six patterns in terms of the relationship between the inundation depths and wash-away rate of the buildings (**Fig. 3**). This made it possible to use tsunami fragility functions (tsunami fragility curves) depending on local properties (coastline shapes, land gradient, and land usage) when deploying real-time tsunami inundation damage prediction system nationwide [5].

3.2. Traffic Simulation (Tohoku University)

The traffic simulation team aims to develop real-time traffic simulation with continuously acquired data (data assimilation) contributing to traffic such as those taken from prove vehicles [6].

The present study analyzed traffic situations during the Kumamoto earthquake in 2016 as a case study for simulating the real-time traffic that occurs during a disaster. By analyzing prove data immediately after the occurrence of the earthquake, the spatiotemporal identification of traffic jam by evacuees in Kumamoto city was performed. Congestion links were detected throughout the entire road network to detect congestion. This study provided important insights such as the issue of rapid traffic congestion cancelation for transferring between cities. In particular, traffic from Fukuoka city to the center of Kumamoto city was significantly affected when the Kumamoto earthquake occurred. A one-hour driving route in normal conditions required more than four hours on a detour because of the blockage of the Kyushu Expressway. It was indicated that congestion could be identified for each destination; movements to shelters, stores, and gas stations increased rapidly after the earthquake occurrence and movement to public paths and other facilities increased after a while.

Based on these analysis results, 12 challenges were clarified as urban traffic challenges during a disaster. Refer to [7] in this special issue for details.

3.3. Remote Sensing (Chiba University, Tohoku University)

The disaster remote sensing team has developed a damage extraction method based on actual data in relation to synthetic aperture radar (SAR) images [8, 9].

The damage detection method using SAR was applied to the cases of the Kumamoto earthquake in 2016, the Great East Japan earthquake in 2011, and the Nepal earthquake in 2015. It was based on the following approaches: 1) the variation, correlation, and phase variation of backscattering coefficients for an image pair before and after the disaster (or multi-temporal images) corresponded to the building damage level [10, 11]; 2) damage extraction using machine learning from training data including images taken after a disaster and actual damage data [12]. ALOS PALSAR-2 images are important in identifying large-area damage in Japan, and were prioritized in the analyses to address future disaster in Japan.

A total detection accuracy of approximately 60% was achieved using image pairs before and after a disaster in the case study of the Kumamoto earthquake by associating variation, correlation, and phase variation of backscattering strength with building damage level [10]. Advancements in the analysis methods using ALOS PALSAR and terraSAR-X data taken during the Great East Japan earthquake enable better analysis technology for quantitative tsunami damage. Thus, a difference and correlation coefficient for backscattering strength before and after a disaster and a regression expression for building damage rates was proposed [11].

On the other hand, a damage extraction method that does not require an image pair to be captured under the same shooting conditions is required because it is difficult to take images before and after a disaster under the same conditions. By effectively using mechanical learning, the building damage in Kathmandu, which was affected by the Nepal earthquake in 2015, could be extracted [12].

In the future, by combining multiple sensors and multiple analysis methods, a flexible technology that can identify large-area damage under conditions immediately after a disaster will be established.

3.4. Emergency Vehicle and Wide-Area Evacuation (Tokyo Institute of Technology)

The emergency vehicle and wide-area evacuation support team integrated simulation models that describe urban damage such as fire spread and road blockage and fire-fighter actions that examine measures against multiple fires during a major earthquake [3, 4]. This enabled the study of fire-fighter action strategies and their effectiveness in reducing the number of burnt-out buildings and fire spread.

First, fire spread simulation was performed under the assumption that each building in the entire Tokyo area catches fire. The fire potential was evaluated in terms of the fire spread hazard index and the limit of the arrival time to prevent a fire from spreading.

Next, fire-fighter actions in affected urban areas during a major earthquake were simulated to estimate the arrival time to burning buildings under four action strategies. Whether a fire was prevented from spreading was judged from the estimate of the number of burnt-out buildings. This is turn was evaluated using the arrival time limit and the actual arrival time. Hence, the effective fire-fighter action strategies were studied. In the case of temporal waiting, which refers to the policy of dispatch destination determination of the Tokyo Fire Department, the number of burnt-out buildings was barely reduced compared to the case of dispatch in the order of report. This is because little information is available within the short waiting time of 15 minutes. On the other hand, when optimal dispatch criteria for each jurisdiction were determined based on the fire spread potential distribution and the reference number of fires, the number of burnt-out buildings was effectively reduced. In addition, by identifying locations of road blockage, the arrival time to the fire was reduced, which reduced the number of burnt-out buildings caused by failed fire-spread prevention by approximately half [15].

Next, the effectiveness of action strategies according to the earthquake scale was investigated. In the case of small-scale earthquakes with a small number of earthquakes, there is no difference among strategies because fire-fighters could arrive at all fires regardless of the strategy. On the other hand, in the case of M8 level large earthquakes, the effect of reducing the number of burnt-out buildings through optimization within the jurisdiction was significant. However, the actual evaluation results were slightly low because some fire-fighting teams remain waiting owing to more stringent immediate dispatch criteria [16].

3.5. Disaster Data Acquisition and Use Environment (The University of Tokyo)

The disaster data acquisition and use environment development team verified the effectiveness of the method for identifying disaster situations involving residents (users) [17] in collaboration with the evacuation action simulation results studied by the emergency vehicle and large-area evacuation support team including Osaragi et al. [13, 14]. From analyzing the outcomes, a basic approach using fire sensing technology and geo-cast communication technology was developed to identify real-time damage situation using cloud sensing at disaster sites.

Earlier, fire information transmission technology used fire alarms as a fire sensing technology. This system consists of three elemental devices: alarms that detect a fire, Internet of Things (IoT) devices that transmit information, and smart phones that acquire location information. It is assumed that commercially available fire alarms are installed in households. IoT devices that connect to fire alarms collect information using sound sensors that detect the sound of alarms and transmit information to smart phones by air. In this study, the Intel Edison that can process sensor data and includes a Bluetooth module was used. The standard "iBeacon," which is superior in advertise (one-way) communication and energy saving as it uses the Bluetooth Low Energy (BLE), was used to transmit information to the smart phones of those who pass by the building using Intel Edison Module. Finally, the smart phone that receives the transmitted information acquires location information using the GPS system. Currently, except for sound transmission from an alarm to the device, only information transmission from the device to those who pass by is considered.

In system evaluation tests, the error level of location information was studied after the iBeacon information transmitted from a residence was detected by a smart phone. The results show that location information was obtained with error levels below 20 m at all transmission intervals of iBeacon [18].

3.6. Big-Data Assimilation (The University of Tokyo)

The big data assimilation development team created distribution of humans and cars assuming various scenarios during a disaster by means of data assimilation using real-time observation data [19, 20]. Preliminarily, the model verification was performed to predict movements of those having difficulty in reaching their residences. This was based on the location information of one million cell phone users in urban areas, and considered wind and water disasters, and mid-scale earthquakes that occur relatively frequently as case studies. In particular, a prediction model was investigated that focuses on "irregularity" of movements after the occurrence of a typhoon disaster in urban areas.

The generation of "irregularity" (variations of movement speeds compared to the normal condition) from mechanical learning was predicted using information consisting of one million locations from cell phones since October 2014. In particular, the kinds of dominant explanatory variables for 18 variables were studied when movement patterns in the normal condition, local characteristics, and disaster characteristics were deemed important in the regression equation.

On verifying the model, the prediction accuracy of irregularity for those on the move in Tokyo owing to disaster occurrence was as high as 64.8% on average. This indicates the possibility of predicting individual movement after a disaster in urban areas using this prediction model.

3.7. Simulation-Data Warehouse (Nagoya University)

The Simulation-Data Warehouse development team proposed the concept of a simulation-data warehouse (SimDWH) that stores, integrates, and organizes a vast amount of simulation data and enables advanced real-time analysis, information transmission, and visualization. The team developed and implemented system technology in collaboration with other teams. In order to organize SimDWH requirements and basic technology, a mock-up was created for a small-scale system with limited functions. Data of evacuation simulation during disasters in Kochi city was incorporated into the data warehouse using the RDBMS data warehouse function (Microsoft SQL Server) [22] as a case study.

The necessity for a SimDWH is addressed in analyzing observation data in the scientific field and simulation data for detecting differences among multiple data related to the same object. When interpreting and analyzing spatiotemporal data stored in a data warehouse, it is important to know the methods to detect variations related to time. In addition, if simulation data with different parameters and observation data with different observation conditions are provided, it is important to know the differences between the different data. The study therefore focused on data difference, which can be considered as a basic analysis requirement in spatiotemporal data warehouse.

For example, the location information of users at different instants of time in 2-dimensional space collected from the GPS system and cell phones is considered as spatiotemporal data. The 2-dimensional space is assumed to have spatial grids, and thus the grid cell corresponding to a given point (x, y) can easily be determined. The implementation of difference calculation uses SciDB, an array-oriented DBMS that specializes in data management and inquiry of large-scale array data in the scientific field.

This effort shows an approach to the implementation of difference calculation (refer to [23] in this special issue for detail). In addition, the effectiveness of this approach was demonstrated by applying this approach to the evacuation human movement simulation data during a tsunami disaster.

3.8. Big-Data Utilization Technology (NIED)

The "Earthquake Hazard Station J-SHIS" shares a vast amount of information obtained by large-scale high-resolution numerical simulation and data assimilation for earthquake and tsunami, and effectively visualizes the obtained data to reduce and prevent disasters for widespread use. Based on this system, technology has been developed to add aggregation and processing functions for large-scale numerical simulation data to the J-SHIS. A prototype of "scenario earthquake waveform data aggregation system" (hereafter referred to as "this system") was created. This system uses long-period earthquake ground motion waveform scenarios calculated using the three-dimensional finite difference method (ten scenarios, 80,000 evaluation points, and three components) as earthquake waveform data from the potential Nankai Trough earthquake scenarios. The waveform data were organized according to each scenario and evaluation point to calculate the earthquake ground motion index for each. The results were aggregated into statistical values at each evaluation point and output as GIS raster data [24].

This study investigated methods for extracting the relationship between local characteristics of ground motions and simulation results. The output is provided as a layer for multiple earthquake scenarios in a parallel-distributed processing system. The extraction method is based on two-stage clustering: clustering of earthquake scenarios in each evaluation grid with data on earthquake ground motion index values and scenario parameters as input;

and clustering of grids based on the similarity of earthquake scenario clustering. By examining the relationship between grid clusters and scenario clusters, the relationship between local characteristics of earthquake ground motions and scenario parameters can be extracted as grid clusters correspond to the geo-space. In addition, results are visualized in GeoTiff image format. The long-period earthquake ground motion simulation data for the Nankai Trough earthquake was applied to the system to confirm that the relationship between extracted local characteristics of earthquake motions and scenario parameters are in accordance with the simulation results for earthquake motions [25].

4. Summary

This paper reported the latest outcomes of the project "Establishing the Advanced Disaster Reduction Management System by Fusion of Real-time Disaster Simulation and Big Data Assimilation" that was launched in 2014.

Several case studies were performed in Kochi prefecture and Tokyo central area, both of which are affected by future earthquakes and tsunamis. The simulation elements included tsunami inundation and damage estimation, evacuation, and traffic, fire, and emergency vehicles. A base for simulation assimilation was constructed using real-time human movement data and sensor data, and verified using data obtained during the Great East Japan earthquake. In addition, analytical approaches, methods, and the validity of systems were examined based on recent disasters to develop and modify elemental technology. This special issue includes reports on latest verification cases.

At the same time, advancements took place in model modification in the field of simulation of "social dynamics," such as movements of humans and cars in response to advanced simulation of "hazard."

Finally, in order to extract scenarios with high likelihood from a vast amount of simulation data, a simulation-data warehouse (SimDWH) was constructed. This stores, integrates, and organizes a vast amount of simulation data to achieve advanced real-time analysis, information transmission, and visualization.

Research on each elemental technology is proceeding smoothly. In the future, model integration will be performed to create a basis for real-time simulation and big data analysis with main cooperative researchers. In particular, a framework will be developed to integrate multiple simulation elements, sensing observation data acquisition, damage prediction, and analysis, which will output data related to earthquakes in the Nankai trough and Tokyo Metropolitan Area.

Acknowledgements

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Name:
Shunichi Koshimura

Affiliation:
Professor, International Research Institute of Disaster Science, Tohoku University

Address:
Aoba 6-6-03, Aramaki, Aoba-Ku, Sendai 980-8579, Japan

Brief Career:

2000-2002 JSPS Research Fellow

2002-2005 Research Scientist, Disaster Reduction and Human Renovation Institute

2005-2012 Associate Professor, Graduate School of Engineering, Tohoku University

2012-present Professor, International Research Institute of Disaster Science, Tohoku University

Selected Publications:

- E. Mas, B. Adriano, and S. Koshimura, "An Integrated Simulation of Tsunami Hazard and Human Evacuation in La Punta, Peru," Journal of Disaster Research, Vol.8, No.2, pp.285-295, 2013.
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Academic Societies & Scientific Organizations:

- Japan Society of Civil Engineers (JSCE)
- Institute of Social Safety Science (ISSS)
- Japan Associaiton for Earthquake Engineering (JAEE)
- Japan Society for Computational Engineering and Science (JSCES)
- Americal Geophysical Union (AGU)