AI with Super-computed Data for Monte Carlo Earthquake Hazard Classification

Tsuyoshi Ichimura[1,2], Kohei Fujita[1,2], Takuma Yamaguchi[1],
Muneo Hori[1,2], Maddegedara Lalith[1,2] and Naonori Ueda[3]
[1]Earthquake Research Institute & Department of Civil Engineering, The University of Tokyo
[2]Advanced Institute for Computational Science, RIKEN
[3]Center for Advanced Intelligence Project, RIKEN

***Abstract*—**Many problems associated with earthquakes are yet to be solved using heroic computing, which is defined as computing at the largest scale possible using the best supercomputers and algorithms. Thus, a continuous effort has been pursued in HPC to solve these problems. However, even when heroic computing is applied, its practical use is difficult without considering the uncertainties in models. In this study, we constructed an AI methodology that uses super-computed data generated using heroic computing. We applied this AI to an earthquake hazard classification including uncertainty analyses in order to demonstrate its utility. This study can be regarded as an innovative step towards realizing high quality computing for Earthquakes by exploiting the potential of HPC through AI.

I. Introduction

Evaluation of earthquake damage scenarios (i.e., estimation of damage to cities and buildings) is required to effectively mitigate the devastating effect of earthquakes. Knowledge of the distribution of earthquake shaking (i.e., the earthquake hazard) at the ground level of whole cities with an area of 100 km^2 is required to generate these damage scenarios (e.g. [1], [2]). Because the soil at a depth of 100 m from the surface consists of soft soils having complex geometry that changes every 10 m, ground shaking due to earthquakes becomes highly nonlinear and varies significantly with local position (e.g. [3]).

To improve earthquake mitigation scenarios, earthquake hazard maps of whole city areas should be developed at a very high resolution (less than 50 m). An approach to generate such hazard maps is to use observed ground shaking data; however, this approach is difficult to implement at such a high resolution. Three-dimensional ground information is currently being accumulated for whole urban areas with the objective of improving earthquake hazard distribution estimation (e.g., [4]). Simulations that use such data can be useful for generating hazard maps; however, this requires a very large-scale analysis, which will be very challenging to accomplish. In addition, subsurface ground cannot be measured directly and will therefore not be highly accurate. The uncertainty of this data must be quantified in the hazard maps. As ground responds highly nonlinearly during earthquakes, conducting Monte Carlo simulations are suitable for considering uncertainty of data; however, this is currently impractical because it requires 10^2 – 10^3 repetitions of a large-scale analysis.

In this study, we develop a practical approach to enable uncertainty analysis of large-scale analyses. Here we enable the above super-large scale analysis by heroic computing, and use this super-computed data to construct an AI methodology. This AI methodology is applied to conduct Monte Carlo simulations to estimate the uncertainty of the results. Even if HPC were to enable large scale analysis with verified results, this would not be sufficient to qualify as high-quality computing (HQC) without the estimation of uncertainty. By considering uncertainty thorough AI, the importance of HPC that enables heroic computing is strengthened. Thus HPC can contribute towards accomplishing HQC for Earthquakes.

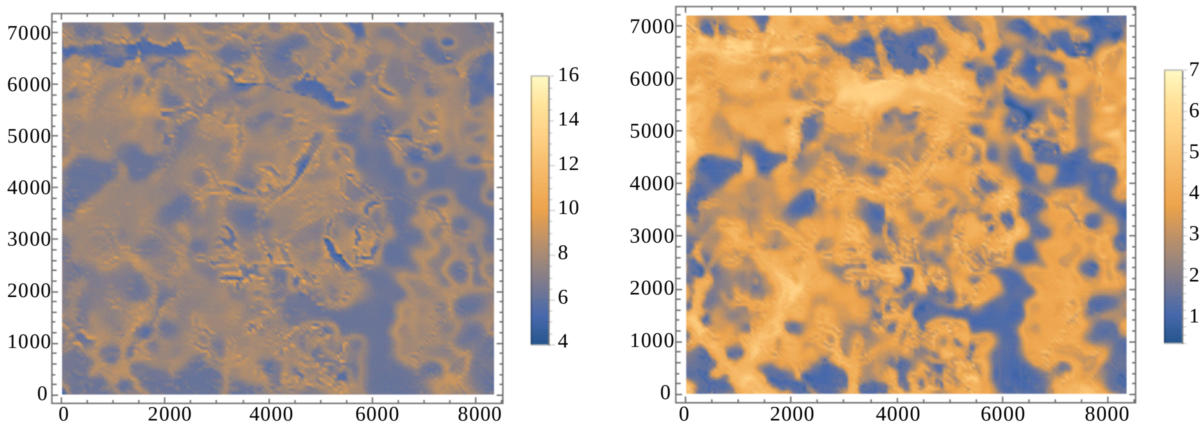
II. AI with Super-computed Data for Monte Carlo Earthquake Hazard Classification

To analyze the distribution of surface ground shaking in a city, it is necessary to obtain the solution to the nonlinear wave equation for the ground for the whole area, i.e., Eq. (1). We use a low-order unstructured finite element method because it analytically satisfies the traction-free boundary condition and is suitable to accurately model complex ground structures with strong local nonlinearity. We use implicit time integration to keep the analysis stable. Because low-order elements are used, this becomes a challenging computation that is dominated by sparse matrix computation with random access.

$$\left(4/dt^2\mathbf{M} + 2/dt\,\mathbf{C}^n + \mathbf{K}^n\right)\ \delta\mathbf{u}^n = \mathbf{f}^n - \mathbf{q}^{n-1} + \mathbf{C}^n\mathbf{v}^{n-1} + \mathbf{M}\left(\mathbf{a}^{n-1} + 4/dt\,\mathbf{v}^{n-1}\right), \quad (1)$$

where, $\delta\mathbf{u}$, $\mathbf{u}$, $\mathbf{v}$, $\mathbf{a}$, $\mathbf{q}$, and $\mathbf{f}$ are incremental displacement, displacement, velocity, acceleration, internal force vectors, and external force vectors, respectively; $\mathbf{M}$, $\mathbf{C}$, and $\mathbf{K}$ are the consistent mass, damping, and stiffness matrices, respectively; and dt and n indicate the time step increment and time step number. For Tokyo, Eq. (1) becomes the order of 0.1 trillion degrees of freedom (DOF), which requires to be solved for each of the 6,000 time steps. This size is considered to be very challenging.

To enable such a massive analysis, we developed a fast and scalable solver [5] using the adaptive conjugate gradient method, mixed precision arithmetic, a multi-grid method, an element-by-element method, structuring of an unstructured mesh, and steady and contiguous memory access computation. This solver attains high performance up to the full K computer system with 663,552 CPU cores on problems with up to 1.08 trillion DOF. This study was nominated as an SC15 Gordon Bell Prize finalist and is presently considered to be state-of-the-art analysis. Using this supercomputing method, we analyzed earthquake ground shaking in a 10,250 m $\times$ 9,250 m area of Central Tokyo. This is the state-of-the-art heroic computation with 0.133 trillion DOF and 6,600 time-steps, which have been solved using the full system of K computer with a maximum user time of 8 hours. A large domain with strong nonlinearity was solved at a high spatial resolution of 1 m; the total data size analyzed was 0.133 trillion DOF $\times$ double precision $\times$ 6,600 time steps = 6,600 TB.



a) Distribution of mean

b) Distribution of 3σ

Fig. 1. Monte Carlo earthquake hazard classification using an AI with super-computed data. Both the mean and 3σ (σ is standard deviation) differs locally.

It is not practical to conduct 1,000 cases of heroic computing to estimate the effect of uncertainty of the ground structure. Thus, using super-computed data, we constructed an AI methodology that classifies ground motion severity and use this AI to conduct Monte Carlo simulation. Here, the ground motion is classified into 20 levels for 50-m grid points inside 8,350 m $\times$ 7,200 m (24,360 points) area of Central Tokyo. It is essential that the developed AI methodology possesses the ability to perform classification with high correct ratios. Generally, nonlinear wave propagation problems are sensitive to the structure within one wavelength of the observation point. Thus, we assume this physical point of view to select and normalize data for training a highly accurate AI system. Here, we conducted training by Chainer [7] on Pietra (SGI, Tesla P100 $\times$ 4, Intel E5-2690 v4 $\times$ 2). Using this AI, we conduct Monte Carlo earthquake hazard classification. The target ground structure consists of three layers; we change the geometry of the interfaces between the first and second layers and that of the interface between the second and third layers using a normal distribution with a mean of 0 m and a standard deviation of 5 m on a 1,000 m grid. We conduct a Monte Carlo simulation with 1,000 samples on this stochastic model using the constructed AI. Fig. 1 shows the mean and standard deviation of the obtained distribution. We can see that both the mean and the standard deviation differ largely from location to location. Such information cannot be obtained by a single case of heroic computing; thus, the distribution was first evaluated via uncertainty analysis using AI; this shows the effectiveness of our method. Because construction of an AI methodology with high correct ratios requires super-computed data obtained from heroic computing, the contribution from HPC was essential for enabling this analysis. From this point of view, we can say that we have revealed the potential of HPC with the development of such an approach.

III. Concluding Remarks

We performed heroic computing using our proposed supercomputing method and developed an AI methodology based on the the obtained super-computed data; this methodology was made highly accurate by selecting and normalizing the training data with the consideration of the underlying physical characteristics of the ground motion problem. We used this methodology to conduct a Monte Carlo earthquake hazard classification procedure and demonstrated the effectiveness of our methodology. In the future, we plan to improve both the AI methodology and the settings for the problem to further improve the performance of our analysis.

Because this problem is highly nonlinear, the resulting distribution becomes very complex. Thus, it is important to consider uncertainty for this problem. On the other hand, it is evident that conducting 1,000 cases of heroic computing using the full K computer with the maximum available time for each case is highly impractical. Many of other earthquake problems are highly nonlinear and results in complex responses. Although we cannot completely eliminate the need for multiple simulations, we have shown that an AI that can confirm attainment of a permissible level of accuracy can enhance HPC via an uncertainty analysis. This demonstrates the potential of HPC and is a big step toward achieving of HQC for earthquakes.

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