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Integrated Earthquake Simulation for Hazard and Disaster Assessment of Urban Area Using High Performance Computing

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Abstract

Integrated earthquake simulation (IES) is a seamless simulation of analyzing the seismic wave propagation process and the structural seismic response process. A model of high fidelity is constructed for an urban area; a three-dimensional model of underground structures is used for the seismic wave propagation process, and a non-linear model is constructed for each building or structure which is located in a target area. Large-scale numerical computation is inevitable for these models of IES; for instance, the underground structure model has more than 100,000,000,000 degree-of-freedoms and the number of the structures is of the order of 100,000. High performance computing is thus employed. Demonstrative examples of IES which are obtained by using K computer, the world 4th fastest supercomputer, are presented. The target is Tokyo which is threatened by a next Tokyo Metropolis Earthquake. Explained are two simulations of analyzing the ground motion amplification process that accounts for non-linear soil properties, and analyzing the seismic responses of residential buildings the models of which are automatically constructed by using available digital data. The possibility of making hazard and disaster assessment using IES is discussed based on these examples.

Keywords: integrated simulation, earthquake hazard and disaster estimation, high performance computing

1. Introduction

The development of a system for the earthquake hazard and disaster assessment has been a major task of earthquake engineering; see HAZUS and GEM [1, 2]. The system calculates an index of strong ground motion using an attenuation equation, and then estimates a probability of structure damage applying fragility (or evaluability) curve. The equation and the curve are obtained from the statistical analysis of the past records of earthquake hazards and disasters. The system that makes use of these empirical relations is a unique solution when earthquake hazard and disaster assessment is made for an urban area of a few kilometers in which more than ten thousands structures are located.

The two core elements of the system, namely, the attenuation equation and the fragility curve, are rarely used for other purposes except for the earthquake hazard and disaster assessment of an urban area. Numerical analysis of seismic wave propagation is used for the ground motion distribution for a given earthquake scenario [3-12], and there are many numerical analysis methods for structural seismic responses that are used for the seismic design. Thus, a natural question is whether such numerical analysis methods are used as an alternative of the core elements of the system of assessing earthquake hazard and disaster in an urban area.

As will be explained in the next section, there are the following two major difficulties in using numerical analysis methods for the earthquake hazard and disaster assessment: 1) the limitation of temporal and spatial resolution in the seismic wave propagation analysis; and 2) the need for huge human resources in constructing a large number of structure models using data of limited quantity and quality. Another difficultly one can point out is the limitation of data for constructing a reliable model of a target area. However, the amount of digital information about urban areas is increasing, and we could be optimistic of solving this difficulty.

The research group of the authors have been developing a system of earthquake hazard and disaster assessment that uses advanced numerical analysis methods, applying computational science and engineering to solve the two difficulties mentioned above [13]. The system is called Integrated Earthquake Simulation (IES), as it integrates various numerical analysis components in order to seamlessly simulate the processes of the earthquake hazard and disaster. The core simulations are the ground motion simulation and the urban area seismic response simulation, which, respectively, analyze a three-dimensional underground structure model and a set of non-linear models for all structures in a target urban area [14, 15].

In this paper, we summarize recent achievements of developing IES that are made by applying high performance computing or utilizing a large-scale parallel computer such as K computer in Japan [16]. The contents of the present paper are organized as follows: First, in Section 2, we explain the two difficulties in using numerical analysis methods as an alternative of conventional empirical relations. The use of high performance computing to solve these difficulties is explained in Section 3. Demonstrative examples of IES using high performance computing for the earthquake hazard and disaster assessment are presented in Section 4. The target is Tokyo, Japan, which is threatened by a possibility of being hit by a large-scale intra-plate earthquake.

2. Two Difficulties in Applying Numerical Analysis to Earthquake Disaster and Hazard Estimation

Owing to the progress of computer hardware and software, sophisticated numerical anlaysis methods are being developed and utilized in various fields of science and engineering. In the field of seimology and Earth Science, developed are advanced numerical analysis methods which are able to anlayze the seismic wave propagation process in a large domain of the crustal length scale, together with data assimlation techniques. In earthquake engineering, various numerical analysis methods based on non-linear finite element method (FEM) are widly used in order to analyze structural seismic response for a given ground motion.

There is a limitation of using such sophistcagted numerical anlaysis methods for earthquake disater and hazard assessement of an urban area. As for the numerical analysis method of the seismic wave propagation process, the spatial and temporal resolution is limited. When a model size, or the degree-of-freedom, is fixed, a larger domain analysis ought to have coarser spatial resolution, which results in lower temporal resolution. Hence, it is not an easy task to analyze the seismic wave propagation process from a fault to a target urban area, in the temporal resolution of, say, 10 Hz; if the wave velocity is of the order of 100 m/s, the scale of the spatial discretization is of the order of 10 m to obtain a numerically acurate solution and the model size becomes large.

As for the numerical analysis method of strucrural seismic responses, we have to assure the quality of an analysis model so that the results of the numerical analysis are reliable. Huge humam resources will be needed to manually construct an analysis model for each structure in an urban area. Moreoever, deitaled information about the structures is necessary to construt a reliable model. If such inforimation is not available, an analysis model constructed has uncertanity in model paraters which are related to mechanical or structural properties.

Note that the difficulty of constructing an analysis model is shared by the seismic wave propagation analysis. This is because it needs a three-dimensional model for underground structures which consist of geological or ground layers of distinct configuration and material properties. Precise information about mechanical properties of each layer is required, too.

3. Improvement of IES

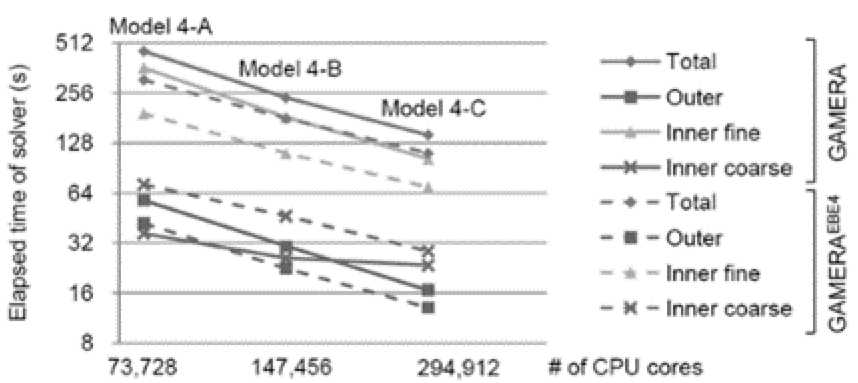
The first difficulty, the limitation of temporal and spatial resolution in the seismic wave propagation analysis in a large domain, is solved just by using a larger-scale analysis model. In IES, we have developed an FEM that is capable to solve a model of more than billions of degree-of-freedom. Numerically analyzing a model of this scale is a challenge in high peformance computing, or *capability computing* that solves a problem of largest scale. Since the seismic wave propagation prcess is a dynamic process, we have to consider a large number of time steps, too; the number of the time step is around 10,000 if a time increment is 0.01 sec and the duration of the process is 100 sec. Therefore, we need an advanced analysis method that is able to fastly solve a problem of a large-scale problem.

It should be pointed out that FEM, rather than finite difference method, is suitable to analyze the seismic wave propagation process, using an anlaysis model of underground structures of high fiedlity, so that topographical effects are readily accounted. For FEM, it is a *solver* (a module of solving a matrix equation) that determines the scale of a solvable problem and the CPU time which is needed to solve the problem. We have developed a fast solver that is able to solve a matrix equation the dimension of which exceeds 100,000,000,000 and to solve one step in the order of 10 sec, to finish the numerical analysis of 10,000 steps in half a day, using K computer [14, 15].

The second difficulty, the need for huge human resources in constructing a large number of structure models using data of limited quantity and quality, is solved by developing a program of automated model construction. In IES, the automated model construction is regarded as data conversion in the sense that digidal data stored in several data resources are processed and converted to digital data of another form in terms of which an analysis model is expresed. Data resources available to the automated morel consturction are of the form of Geographical Infromaty System (GIS) or the form of database, and hence the data conversion is principaplly possible.

It is not expected that complete information that is needed to construct an analysis model is included in the data resources; each data resource has its own purpose, not the construction of an urban area model. Hence, there is uncertainty in parameters of the model due to the data resource limitation. To account for such uncertainity, IES is able to solve 1,000 or more analysis models for one structure, which are generated by the automated model construction system, suitably vayring the model parameters. We have to take advantage of high performance computing, or *capacity computing*, in order to analyze numerous models. Recall that the number of the models will be 1,000,000,000 if there are 1,000,000 structures and 1,000 models are generated for each.

In the following two subsections, we briefly explain the fast solver developed for FEM of analyzing the seismic wave propagation process and the automated model construction system to convert information stored in data resources to an analysis model.



Method	GAMERA			GAMERA^{EBE4}		
Model	4-A	4-B	4-C	4-A	4-B	4-C
Elapsed time of solver (s)	456.6	239.4	143.0	306.3	180.0	111.0
FLOPS/Peak (%)	10.3	9.65	8.19	17.1	14.7	11.8

Fig. 1 – Scalability of solver developed for analyzing seismic wave propagation process; GAMERA and GAMERA^{EBE4} are code names; Total, Outer, Inner fine, Inner coarse stand for the total CPU time, the CPU time of

computing an outer loop solution, an inner loop fine solution, and an inner loop coarse solution, respectively; and Model 4-A, 4-B and 4-C are underground structure models of different size.

3.1 Fast solver of FEM

A conjugate gradient (CG) method is used as an algorithm of solving a matrix equation of FEM when a large-sacle problem is solved [17, 18]; denoting by N the dimension of the matrix, the computation time is $O(N^2)$ for ordinary algorithms, but $O(N \log N)$ for the CG method. Note that the CG method is iterative, as it computes a series of approximated solutions of the matrix equation. The speed of solving the matrix equation by the CG method depends on the number of iteration at which a suitablly accurate solution is obtained and the CPU time of solving each iteration.

The implementation of the CG method into FEM is not difficult. However, to increase the performance of the solver, we need special tunings of the CG method; tunings are made for K comuter which we use for the seimsic wave propagation process. The major tungins are the following two: 1) the geometric multi-grid, in which a coarse solution is first obtained to find a good initial solution of the iteration; and 2) the mixed precision arithmetic that uses variable of low precision to obtain a coarse solution in a most efficient manner.

The scalablity of the solver that is developed for analyzing the seismic wave propagation process is presented in Fig 1; K computer is used for this computation, and the degree-of-freedom for the models analyzed exceeds 100,000,000. As the number of CPU cores increase, the CPU time decreases linearly, which shows good performance of the developed solver. We have to mention that other tunings, such as element-by-elmenet method for efficient memory usage, compressed row storage for efficint communcation, or predictor of higher order, are made for FEM that is used by IES.

3.2 Automated model construction system

The automated model construction system develeoped for IES ought to be flexible so that it is able to handle various data resources and analysis models; data resources are commerical GIS, 3D maps, or inventories operated by local government. Object-oriented programing and aspect-orietened programing are essential in developing the program of the system [19].

A key issue of the autmotated model construciton is how to combine information stored in different data resoruces to make one analysis model. Combining information is principally straightfoward, provided that location infromation of any form such as address, longitude and lattitude, or building index, is included. However, some data resources are made in the form of computer aided design, and the location information is given as a local coordinate of the resource. There are data resouces with which it is difficult to interprete the local coordinate, and there are cases in which inconsistecy is found between information stored in different data resoruces. Automated data extraction from such data resources is not perfectly made, and some manual works are needed.

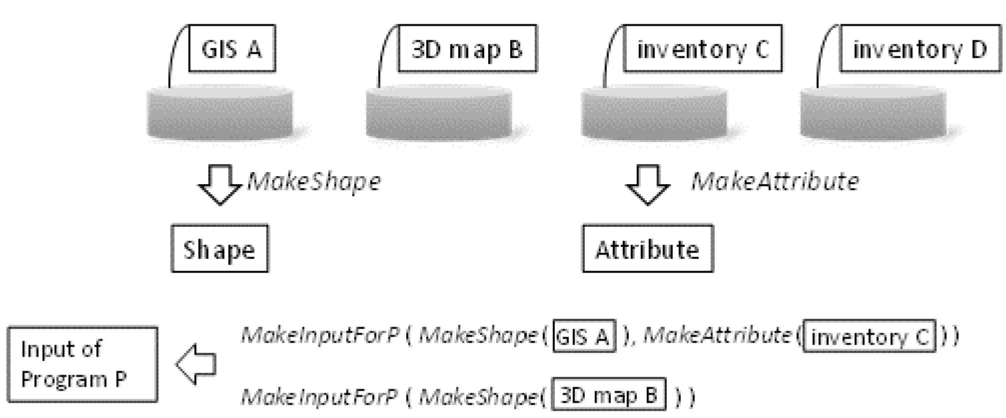


Fig. 2 – Use of automated model construction system; data extraction from data resource is made by using common function and model construction is made by using distinct functions.

The automated model construction gusses model parameters, in order to compenstate missed or unavailable information about a structure. In Japan, a so-clled 3D map is avaialbe for most of major cities, and exact information about configuration of a residnetial building (heigth and floor shape) is extracted from it. IES mostly uses a multi-degree-of-freedom system as an analysis model of a residentialu buidling, and guesses parameters of the stiffness and strength, based on the height of the structure and emperical relations. Suitable emperical relation is chosen when the building type is identified by using available inventory of building type. The building type ought to be guessed based on the height and floor area if such inventory is not available.

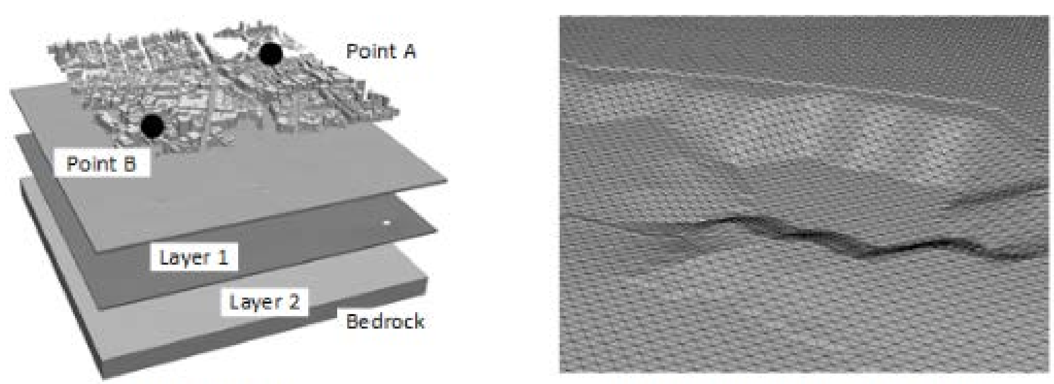
The autmotaed model construction is easily used, as it takes advantage of object-oriented programing and aspect-oriented programing. As shown in Fig. 2, two functions, *MakeShape* and *MakeAttribute*, are used to extract data from any data resources; *Shape* and *Attribute* are an object for structural configuration and building information such as structure type, respectively. A specific function, *MakeInputForP*, is used to construct an analysis model for *Program P*; the argument of this function is a set of *Shape* and *Attribute*, or *Shape* only.

4. Examples of IES Using High Performance Computing

In this section, we present examples of IES using high performance computing. The target is Tokyo, Japan, and commerical and public GIS's are used as data resources. Ground motion amplification near surface layers of few ten meter thickness is analyzed by using the developed FEM. A non-linear multi-dgree-of-freedom system is used as a model of seismic structural response analysis for each residential building, which is automtatically constructed by using the developed automated model construction system.

4.1 Simulation of ground motion amplification

An analysis model of the surface layers is presented in Fig. 3; the domain is 1,250 x 1,250 m, and consists of three layers including bedrock. The number of nodes, elements, and degree-of-freedom are 340,876,783, 252,737,051, and 1,022,630,349, respectively; this scale is necessary in order to assure the numerical convergence up to 10 Hz. This simulation is regarded as capability computing, as the degree-of-freeom exceeds 100,000,000. Ramberg-Osgood mode and Masing rule are employed as a non-linear constitutive relation of soil [20, 21].



model overview

detailed configuration of analysis model

layer property

	V_p (m/s)	V_s (m/s)	ρ (kg/m^3)	h_{max} or h	γ_r
1st layer	1,210	150	1,500	0.25	0.005
2nd layer	1,380	255	1,800	0.05	∞
bedrock	1,770	490	1,900	0.005	∞

Fig. 3 – Analysis model of surface layers; data resources are JSHIS and National Digital Soil Map [20, 21]

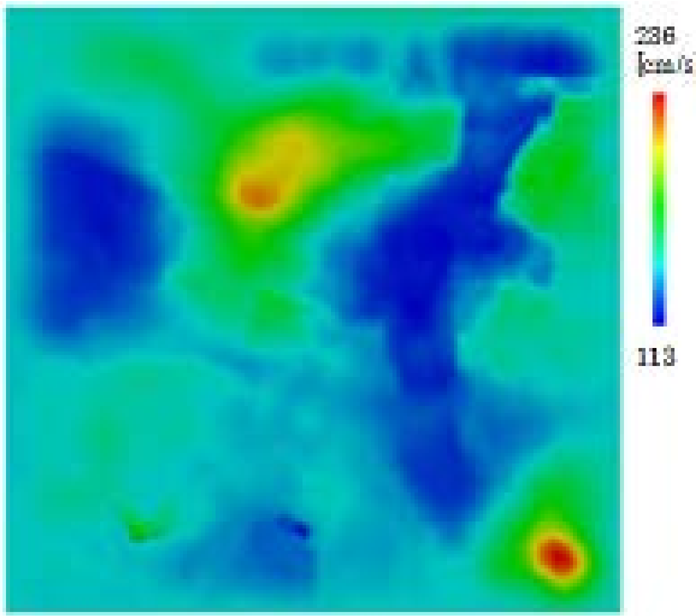


Fig. 4 – Distribution of SI ($\mathrm{SI} = \frac{1}{2.4}\int_{0.1}^{2.4} S_v(T)\,\mathrm{d}T$)

The distribution of SI ($\mathrm{SI} = \frac{1}{2.4}\int_{0.1}^{2.4} S_v(T)\,\mathrm{d}T$) is presented in Fig. 4, when Kobe Earthquake (JR Takatori) is used as input ground motion on the bedrock [22]. It is seen that the distribution is far from being uniform in this area of 1 km x 1 km. As expected, this is due to topographical effects of the three layers, even if the input groun motion is uniform on the bottom of the bedrock layer. There are two spots at which SI is conecnterted; the value of SI exceds 200 kine.

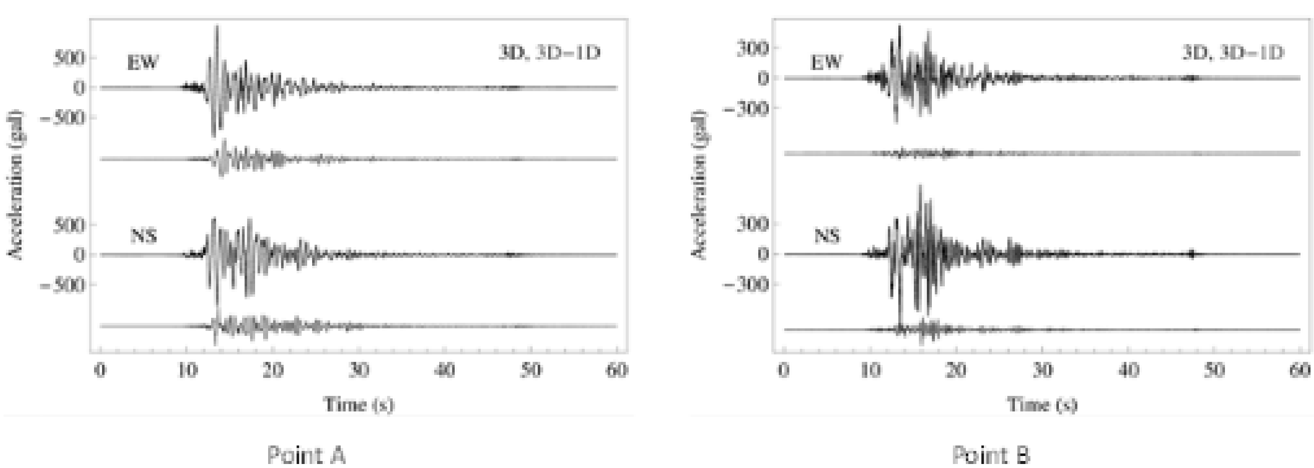


Fig. 5 – Comparison of 3D-analysis and 1D-analysis of ground motion amplification process

Fig. 6 – Distribution of maximum story drift angle

It is of interest to compare the results of capability computing with the conventional analysis that uses a 1D stratified model at a target site. In Fig. 5, the waveform of acceleration in the EW and NS directions is presented; Points A and B shown in Fig. 3 are used for the 1D analysis. While the waveforms at Point B appera similar (with the largest difference being around 30 gal), the difference in the wavefroms at Point A seems substantial (with the largest difference being close to 100 gal). This is due to the topographical effects of local three-dimensional underground structures near Point A. It should be emphasized that capability computing that uses a large-scale model of underground structures enable us to see such large topographical effects.

4.2 Simulation of structural seismic response subjected to in-site ground motion

Therea are 4,066 residential buildings in the area presented in Fig. 3. A non-linear multi-degree-of-freedom system, with the number of the mass being the floor number, is made for each building [24-26]. No inventory of building type is available, and, for simplicity, we assume that all the buildigns are reinforced concrete. Bi-linear model (or perfect elasto-plasticity) is used, and the stiffness and strength are two model parameters. The stiffness is determined from the emperical equation between the first natural freqeuncy and the building height. The strength is determined by using an emperical relation between the stiffness and the stregnth. The weight of the building is computed based on the floor area

The distribution of the maxiumum story drift angle is plotted in Fig. 6. It is difficult to see similarity in the distribution of SI and the maximum story driftangle shown in Figs. 4 and 6. Indeed, the maximu story drift is relatively smaller at the two spots where SI is locally concentrated, and building models which depict local damage are located at sites where SI is relatively smaller. The discrepancy between the ground motion concentration and the building damage is due to the difference in dominat compontns of input ground motion and natural frequency of structures. We can understand that large stroy drift angles of building models are induced by the resonance of ground motion that is locally amplified and the structural dynamic response.

Like the preceding subsection, we examine the nececessiy of making the 3D-analsys of the ground motion amplification process, even for the structural seismic response analysis. The identical analysis models are used for residential buildings, but ground motion input to the model is either the one computed by using the 3D-analysis or the conventional 1D-analysis. The results are presented in Fig. 7; SI's computed by the

3D-analysis, the 1D-analysis, and their difference are plotted in the top three figures, and the the maximum story drift angles based on the 3D-analysis, the 1D-analysis and their difference are ploted in the bottom three figures. As is seen, the difference reaches 40 kine for SI and 0.003 for the maximum story drift angle.

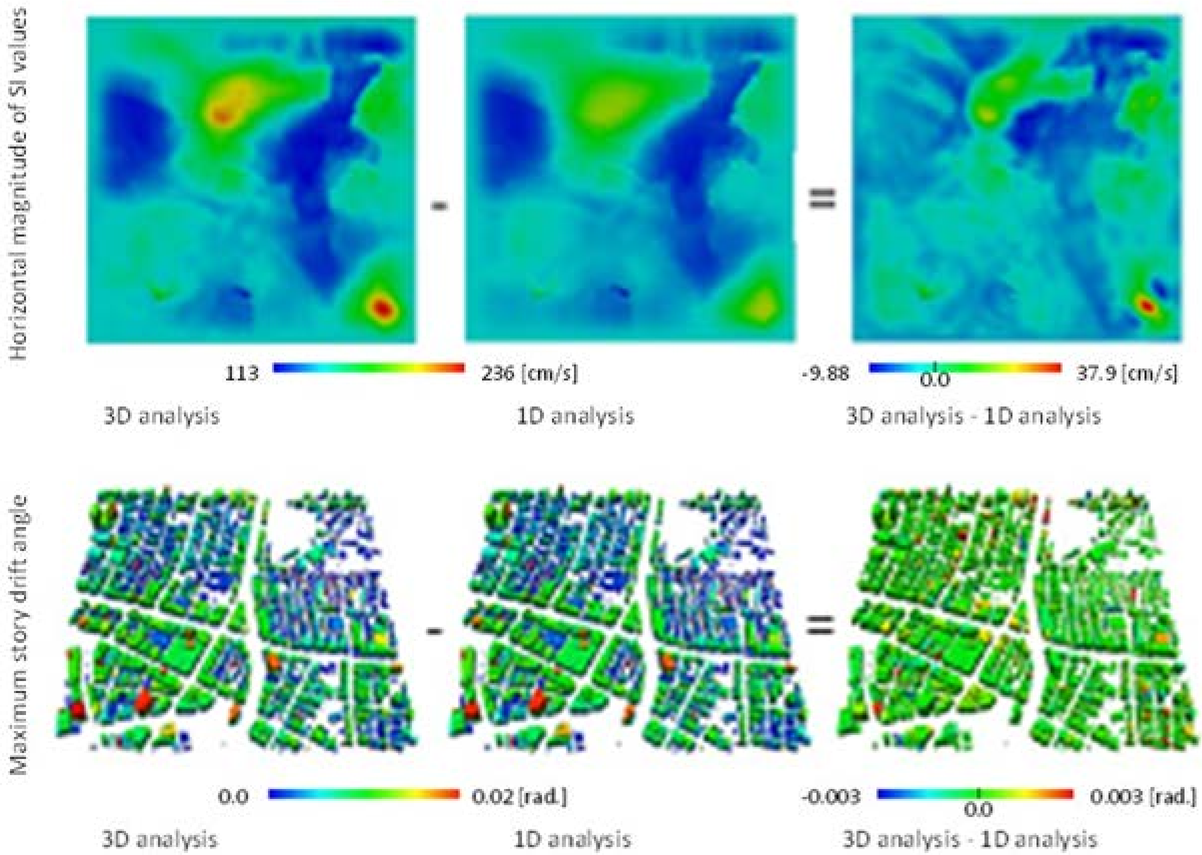


Fig. 7 – Comparison of structural seismic response due to different in-site ground motion of 3D-analysis and 1D-analysis

Due to the lack in relevant data resources, there is larger uncertanity in determing the strength of the bi-linear model, compared with the stiffness. We thus apply capacity computing of generating 10,000 models for each residential building, changing the value of the strength; a normal distribution is assumed for the strength, with the standard deviation being 10 % of the mean. Since the number of the buildings is 4,066, the total number of non-linear analysis model is 40,660,000, and we surely need capacity computing.

In Fig. 8, the mean, the maximum and the standard deviation of the maximum story drift angle are plotted for 4,066 residential buildings. The standard deviation indicates the degree of uncertanity of the present analysis, or the effects of the uncertain model parameter of the strength on the structural seismic response. Due to the non-linearity of the bi-linear model, the standard deviation of the strength (which is 10 % of the mean) produces standard deviation of around 0.01 [rad] for the maximum story drift angle. On the other hand, the maximum response exceeds 0.05 [rad] for some building. As expected, the probabilistic distribution of the response is not normal even though the normal distribution is used for the uncertain strength.

4.3 Combined simulation of ground motion and structural response for 10 x 10 km area

Using K computer, IES is able to make combined simulation of ground motion and structural response for a domain of 10,250 x 9,250 m. This combined simulation is regarded as capability computing since it needs the whole 705,024 compute cores of K computer to finish the computation less than 12 hours for the ground motion analysis; an underground structure model is similar to the one shown in Fig. 3, as it consists of three surface layers but the

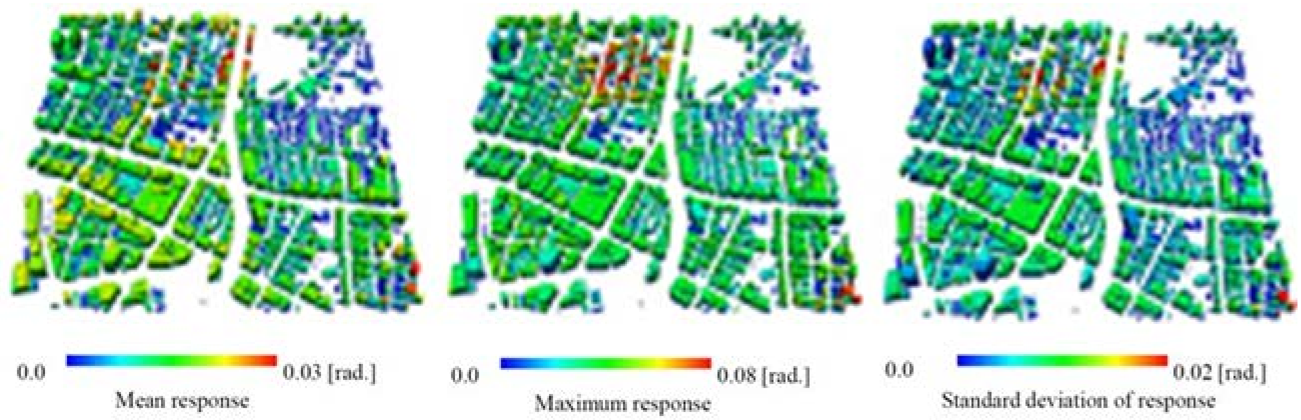


Fig. 8 – Mean, maximum and standard deviation of maximum drift angle using 10,000 models for each residential building

number of degree-of-freedom is 133,000,000,000 and the time step is 6,600 [15]. In this setting, the temporal resolution is 10 Hz, which is assured by examining the convergence of a solution with respect to the model size.

An example of the combined simulation is presented in Fig. 9; there are 32,800 residential building in the target domain, and a multi-degree-of-freedom system is made as analysis model for each building, which is assumed to be a reinforced concrete building. The input ground motion is actually computed by using FEM for an assumed earthquake scenario of Tokyo Metropolis Earthquake [27]. IES evaluates earthquake hazard and disaster in terms of SI and maximum story drift angle, respectively. As explained in the preceding subsection, we need to make capacity computing for the structural response in order to account for the uncertainty in constructing an analysis model due to the limitation of available information. A possible range of resulting disaster will be expressed in terms of the standard deviation of the maximum drift angle if such capacity computing is made.

It should be emphasized that no new findings are made in the combined simulation of IES. It simply applies well-established ground motion analysis and structural response analysis to the entire urban area, by taking advantage of high performance computing. The results of the combined simulation, however, are worth being examined as it produces hazard and disaster assessment in highest resolution. The assessment of earthquake hazard and disaster made by IES is applicable to any other cities in the world, if suitable data resources are available and the automated model construction system generates a suitable model for the city.

5. Concluding Remarks

This paper presents Integrated Earthquake Simulation (IES) for Tokyo, Japan. High performace computing enables us to develop this IES, or a system of making earthquake hazard and disaster assessement based on the numerical simulation. Provided that suitable computaioal environemnt and data resourcs are available, IES is applicable to any urban area. Developed are a finite element method (FEM) that is able to solve a large-scale problem of the seismic wave propagation process and an automated model construction system that converts digital information stored in data resources to models of structurral seismic response analysis.

We are planning to extend IES to social science simulation, such as mass evacuation frtom tsunami, traffic simulation in damaged areas, or ecconomic activities in damaged areas. Social science simualtion must consider numerous scenarios of disasters and recovering processes, and hece it is a good target of capacity computing. It is antoher challenge to apply high performance computing to realize the social science simulation that is needed to increase the resilience of a target area.

Acknowledgements

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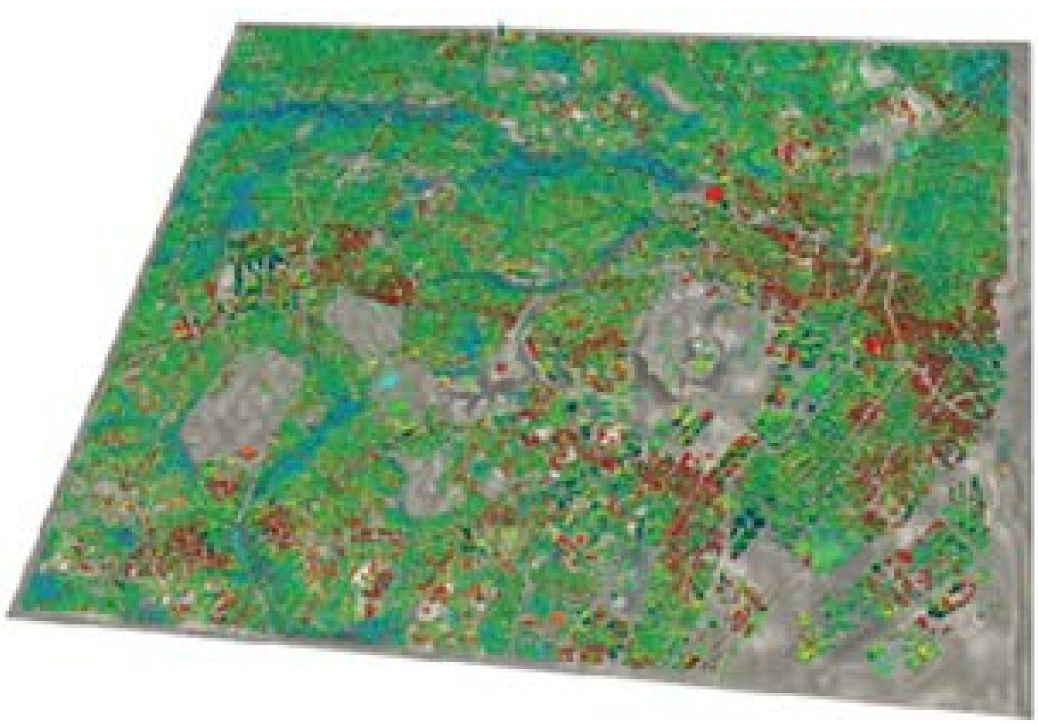

Fig. 9 – Combined simulation of ground motion amplification and structural seismic response analysis for 10 x 10 km area; gray color on ground is SI, and green-to-red color of building is maximum drift angle

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