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APPLICATION OF HPC TO EARTHQUAKE ENGINEERING – SEISMIC STRUCTURE RESPONSE ANALYSIS AND URBAN AREA EARTHQUAKE SIMULATION –

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Abstract. *This paper presents two examples of applying high performance computation (HPC) to earthquake engineering problems. One example is for the seismic structure response simulation, which improves the accuracy of estimating the structure seismic performance. A finite element method which is tuned for K computer is explained and results of trial simulation made in K computer are presented. The second example is for the urban area earthquake simulation. Explained are the urban area seismic response simulation which analyzes seismic response of all the building and the mass evacuation simulation that uses multi agent simulation. Illustrative examples of these simulations are presented.*

1 INTRODUCTION

Seismic design is improved if structure seismic performance is evaluated more accurately; see, for instance, Fardis[1] for the seismic design of concrete buildings. However, accurate evaluation is not trivial, since, for an extremely large ground motion, seismic responses often induce residual deformation but the deformation should not reach the level at which structure collapse happens. Currently, experiments are used for accurate evaluation of seismic performance, though these are time consuming and require sophisticated large experimental apparatus. Numerical analysis will be a substitute, if it is able to evaluate local damage and global failure.

Earthquake disaster assessment[2, 3] is used to make an earthquake disaster mitigation plan for an urban area. A more accurate assessment is required to make a more rational mitigation plan. Unlike the structure seismic performance, the earthquake disaster assessment involves non-physical processes such as mass evacuation, recovery works of damaged structures, and so on. Numerical simulation is a unique tool of evaluating such non-physical processes since no experiment can be made for these processes. It is thus necessary to development reliable codes.

High performance computing (HPC)[4] plays a key role in carrying out larger numerical computation for the accurate evaluation of seismic structure performance and for the accurate assessment of urban area earthquake disaster. This is because more accurate evaluation and assessment requires more sophisticated model and simulation, which inevitably results in larger amount of numerical computation.

The authors have been seeking to apply HPC to two major problems of earthquake engineering, namely, the seismic structure response analysis and the urban area earthquake simulation, which are used for the seismic structure performance evaluation and the earthquake disaster assessment, respectively. In this paper, we present several examples of applying HPC to the earthquake engineering problems, demonstrating the potential of the HPC application.

This paper is organized as follows: first, we summarize our perspective of numerical computation that is currently used in solving the two problems of earthquake engineering. Next, we present recent achievement of applying HPC to solve the problems. For the problem of the seismic structure analysis, developed is a general purpose finite element method (FEM), which is able to solve high fidelity model of a structure subjected to ground motion. For the problem of the urban area earthquake simulation, the urban area seismic response simulation and the mass evacuation simulation are explained.

2 CURRENT STATE OF NUMERICAL COMPUATION IN EARTHQUAKE ENGINEERING

As mentioned, earthquake engineering has two major numerical problems, the seismic structure response analysis and the urban area earthquake simulation. The seismic structure responses analysis is aimed at evaluating structure seismic performance, by considering various factors such as soil-structure interaction, cyclic loading, or local damage and failure. The urban earthquake simulation is used to make a rational disaster mitigation plan, by considering possible structure damages which induce fire, injuries and casualties as well as regional and domestic economic loss.

It is most difficult to numerically analyze dynamic processes of non-linear structure seismic response which could reach local or overall damage. In practice, therefore, used are experimental studies of a scaled model of structure members, and numerical analysis that takes advantage of the experiment results to evaluate the structure seismic performance. As the higher level of accuracy is sought from these experiments, the cost and time required become higher and longer; the number of the infrastructures with required facilities decreases, too.

FEM with solid elements is a substitute of experimental study, if it is able to analyze local damage of a structure. Since the zone of local damages is several orders of magnitudes smaller than the size of a structure, an analysis model is required to consist of multitudes of solid elements. This is the major reason that HPC is needed for the seismic structure response analysis. It should be noted that reinforced concrete (RC) structure shares a large portion of buildings, and hence FEM for an RC structure is a major target of the HPC application. The HPC application should account for the two characteristics of concrete material, namely, complicated elasto-plastic properties and brittle cracking of various sizes.

Urban area earthquake simulation is not a new subject; there are open software for the simulation of ground motion distribution and induced structure damages. The present simulation relies on empirical relations, since it must analyze ground of large area and all buildings located in a target area. Inter- or extrapolation of data of past disaster is also used to make assessment of a possible disaster, provided that the situation at future earthquake will be similar to the one at the past.

If a *physical* model is built for underground structure and a set of building in a target city, processes of ground motion generation and resulting building responses are computed for a given scenario of an earthquake. Such numerical simulation is a good application of HPC, since it requires large amount of numerical computation. A key element is the construction of an urban area model. A sequence of damage such as mass evacuation could be simulated if a suitable model and analysis method is developed. This is a good application of HPC as it is aimed at simulating behavior of all residents in the target area.

3 HPC FOR SEISMIC STRUCTURE RESPONSE ANALYSIS

In this section, we present recent achievement of applying HPC to the seismic structure response analysis. A general purpose seismic response simulation is being developed; it is an extension of an FEM package which has high parallel computation performance. A major target of the simulation is non-linear dynamic responses of an RC structure, and modules of concrete elasto-plasticity and failure analysis are implemented.

3.1 FEM for Structure Seismic Response Simulation

ADVENTURE-K, which is an extended version of ADVENTURE_Solid[6] and specially tuned for K computer, is used for the structure seismic response simulation. We should mention that ADVENTURE_Solid is a general purpose FEM package and has high parallel computation performance in several computer environments. It is a solver that plays a key role in achieving higher parallel computation performance when a large scale model is analyzed; most of computation time is used to solve a matrix equation of FEM. A key characteristic of ADVENTURE-K's solver is a domain decomposition method (DDM) which is specially tuned with preconditioning of balanced domain decomposition (BDD). Most of efforts made to tune ADVENTURE_solid to ADVENTURE-K have been put to improve the solver.

Architecture of a massive parallel computer like K computer (in which around 88,000 nodes each of which has 8 cores are installed) favors structured grid computation rather than non-structured grid computation. FEM has inherent disadvantage in achieving high scalability by taking full advantage of structured communication topology of supercomputers. In view of this, we evaluate the parallel computation performance of ADVENTURE-K's solver as fairly satis-

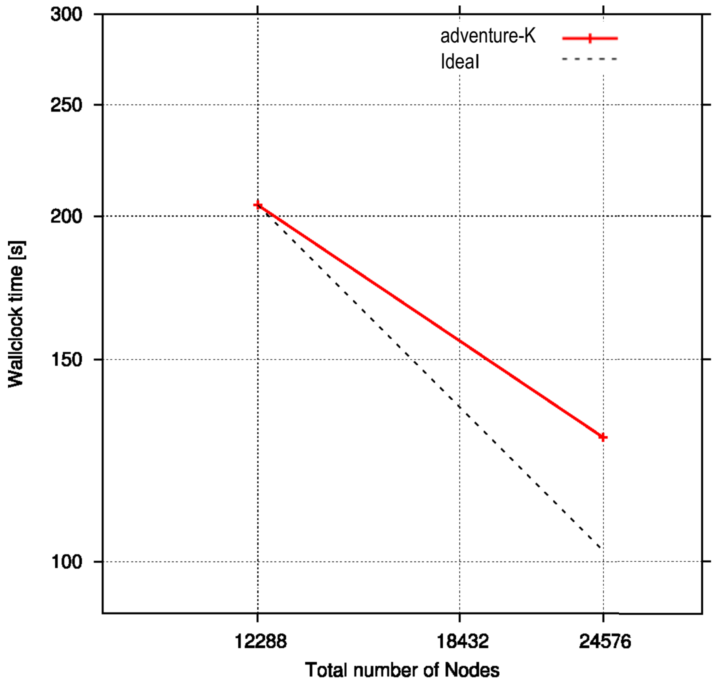


Figure 1: Strong scaling of ADVNENTURE-K in K computer environment.

Table 1: Parallel Computation Performance of ADVENTURE-K in K computer environment.

# Nodes	Total Time(s)	Peak [TFLOPS]	Peak ratio [%]	Efficiency [%]
12,288	204.5	89.7	5.71	-
24,576	128.3	151.3	4.81	79.6

factory in K computer environment, due to the implementation of DDM with preconditioning of BDD. In Table 1 and Fig. 1, basic parallel computation performance of ADVENTURE-K is summarized; the peak speed is 151.3 TFLOPS, which corresponds to the peak ratio of 4.81% of K computer, and the efficiency in strong scaling is 79.7% when the performance of 24,576 nodes is compared with that of 12,288 nodes.

3.2 Example of RC Structure Simulation

A major target of the structure seismic response simulation is an RC structure. Modules which deal with the two characteristics of concrete material (i.e., elasto-plastic constitutive relation and failure analysis) are implemented into ADVENTURE-K. In this subsection, we explain these modules, and present results of numerical computation for a RC pier.

3.2.1 Modules to deal with concrete material

Elasto-plastic constitutive relation which depends on confining pressure and loading history is a key characteristic of concrete material. The relation developed by Maekawa *et al.*[7] is used since it is known as one of the most accurate and reliable relations in the field of concrete engineering. To implement this constitutive relation into ADVENTURE-K, we have to make the following two efforts[8]:

Table 2: Material properties of sample of shear connector experiment.

	concrete	steel
Young modulus [MPa]	21820.0	208000.0
Poisson ratio	0.3	0.29
yield stress [MPa]	-	370.0
hardening [MPa]	-	2080.0
compressive strength [tMPa]	21.4	-

1. Reformulation of the constitutive relation in the form that correspond to standard rate form of elasto-plasticity.

2. Development of a new algorithm to solve the elasto-plastic constitutive relation.

The reformulation makes it easy to implement the constitutive relation into the code. The new algorithm is essential since the constitutive relation of concrete has a negative slope between strain and stress increments after concrete reaches its maximum strength; the negative slop results in the loss of the positive-definiteness in the matrix of the discretized equation and the conjugate gradient method is not applicable.

Initiation and propagation of cracks of various sizes is a key characteristic of concrete material. Crack surfaces observed in concrete are complicated, and it is difficult to apply ordinary numerical analysis method, such as extended FEM[9] or element-free Galerkin method[10], to compute cracks of such complicated configuration. We employ a new discretization scheme, called Particle Discretization Scheme (PDS)[11, 12], to discretize a displacement field with discontinuities that correspond to cracks. This scheme uses a set of discontinuous basis function and bifurcation and branching of discontinuities is easily expressed. The failure analysis that uses this scheme is straightforward as it easily computes the crack initiation and propagation by using the inherent discontinuities of the basis functions.

3.2.2 Trial numerical simulation of shear connector

In order to examine the usefulness the two modules of the elasto-plastic constitutive relation and the failure analysis, we make trial numerical computation of a shear connector problem; a shear connector is used to connect two RC structure members, and its capacity is strongly influenced by non-linear elasto-plastic deformation as well as cracking which stems from the connector. A schematic view of a shear connector problem is presented in Fig. 2 which is an experiment sample[13], and Table 2 summarizes the material properties of the experiment sample.

In the numerical computation, studied are the effects of smoother which is put in the interface between the RC slab and the main beam and the effects of re-contact of cracked concrete. Smoother decreases shear friction on the interface; shear friction on the interface may lead to cracking in concrete near the interface; and re-contact transmits stress in cracked concrete, which, in our view, is a mechanism of concrete near the connector to hold concentrated stress. The results are shown in Fig. 3; a) gives the load-displacement curve when the smoother is included, and b) is cracking pattern when re-contact is included. As is seen, introducing smoother, we can improve the agreement of the synthesized load-displacement curve with the experimental data. Also, re-contact of cracked concrete spatially distributes the initiation of cracks near the shear connector, which appears more realistic.

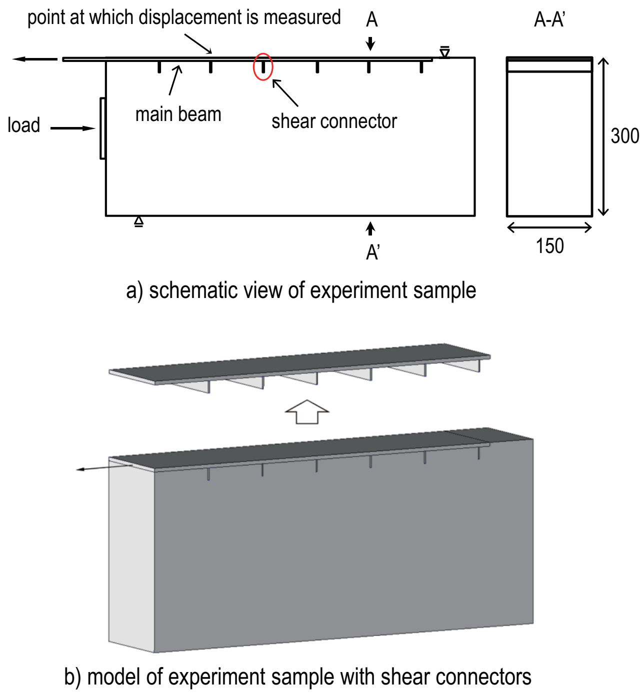


Figure 2: Experiment sample for shear connector.

A typical cracking pattern is presented in Fig. 4. Cracking takes place at the tip of shear connector, and each crack has its own length and arc length. The pattern of this cracking is similar to the one observed in the experiment.

The major role of shear connector is to transmit force between two RC structure members. The numerical simulation is thus required to reproduce the dependence of the transmitted force on the properties of the shear connectors. In Fig. 5, the dependence of the transmitted force via the shear connector on its number and spacing is plotted and compared with the experimental results; smoother and re-contact are used in the simulation. As is seen, the agreement of the numerical simulation with the experiment data is satisfactory in a wide range of the number and spacing of shear connector. We should emphasize that these results are reproduced by FEM analysis of massive solid elements, which requires small scale experiments in order to determine material properties.

3.2.3 Numerical simulation RC pier

Since the trial simulation produces good results, we move to study the seismic performance of an RC pier, using ADVENTURE-K. We have to emphasize that no validation is made to the results of the present simulation unlike the trial simulation. We are planning to make validate the simulation results with the experiment data made in E-DEFENSE[14], a shaking table that is operated by National Research Institute for Earth Science and Disaster Prevent, Japan; the pier analyzed in this simulation is the one that was used in an actual experiment of E-DEFENSE. An analysis model consists of an RC pier (which is the combination of concrete and reinforcemenet), its pile foundation and surrounding soil, so that soil-structure interaction effects are fully taken into consideration. The analysis model and the material properties are summarized in Fig. 6 and Table 3, respectively. As is seen, all the components of the RC pier are densely discretized.

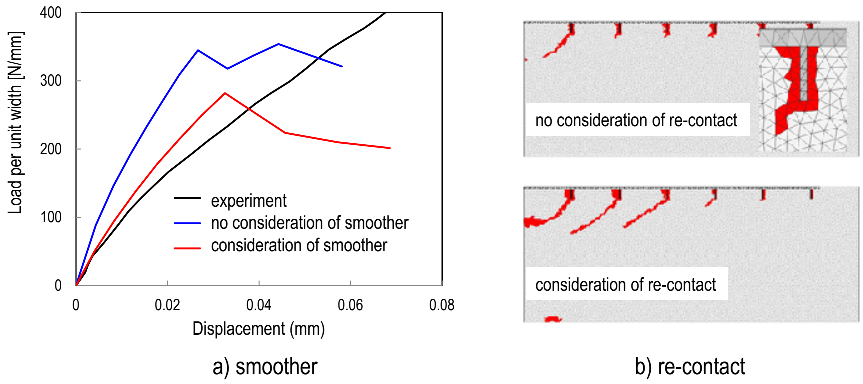


Figure 3: Effects of smoother and re-contact.

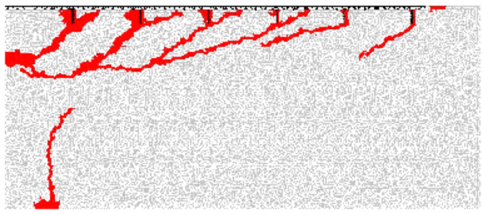


Figure 4: Pattern of cracking; a crack is initiated from each shear connector and extends.

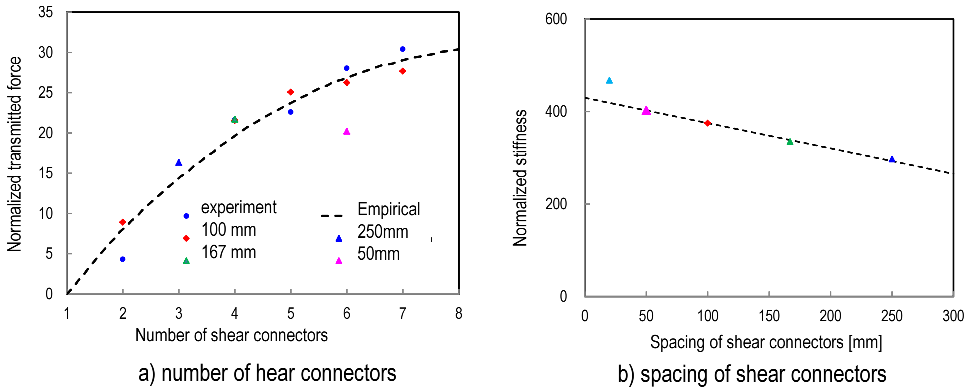
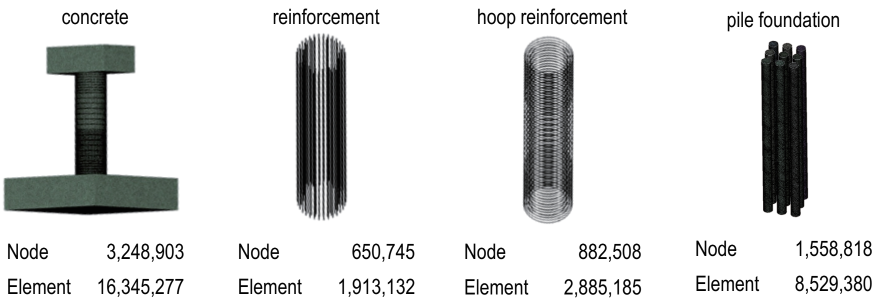


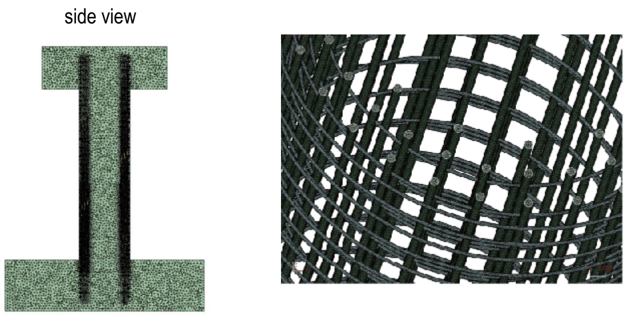
Figure 5: Dependence of transmitted force on shear connector.

Table 3: Material properties of RC pier.

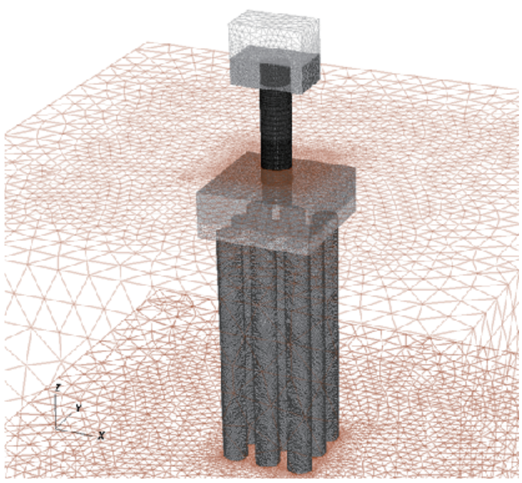
	concrete	steel
Young modulus [kN/mm^2]	25000.0	200000.0
Poisson ratio	0.3	0.3
hardening [kN/mm^2]	1000.0	20000.0
yield stress [kN/mm^2]	30.0	350.0
density [ton/mm^3]	2.3e-0.9	7.5e-0.9



a) major parts of RC pier



b) details of reinforcement



c) whole view of RC pier model standing on its pile foundation embedded in soil

Figure 6: Analysis model of RC pier.

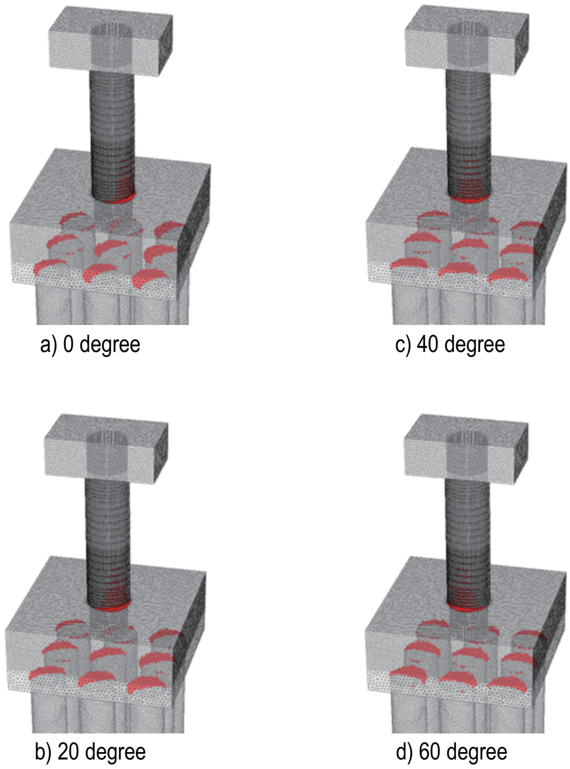


Figure 7: Cracking pattern of RC pier subjected to ground motion at different input angle.

An advantage of applying HPC to the structure seismic response simulation is the fact that it allows us to study a detailed model as shown in Fig. 6 which has a large number of degree-of-freedom. As another advantage, we point out that it allows us to accurately evaluate the seismic performance of a structure, by considering various cases of input ground motion. Experimental study surely has limitation in the number of experiment samples, unlike numerical study in which we can reuse one analysis model several or many times. In the present simulation, we study the performance of the RC pier subjected to JR Takatori ground motion, which was observed in 1995 Great Kobe Earthquake, by changing the direction of the ground motion.

As an illustrative example of the numerical simulation for the seismic performance evaluation, we present cracking pattern of the RC pier due to different input ground motion in Fig. 7. As is seen, the location of cracked concrete (the crack surfaces are colored in red) change as the direction of the input ground motion changes. While the area of the crack surfaces appears more or less the same even when subjected to input ground motion of different direction, it is not identical. As expected, the structure behavior is not *isotropic*, in the sense that the behavior changes depending on the loading direction. Due to this anisotropy, therefore, more accurate evaluation of the seismic performance can be made by analyzing the seismic response with various input ground motion. HPC is surely an important element to realize such numerical simulation which requires large amount of numerical computation as well as efficient and fast computation for practical purpose.

4 HPC FOR URBAN AREA EARTHQUAKE SIMULATION

Unlike the structure seismic response simulation, there are few numerical analysis methods which can be used for urban area earthquake disaster assessment. This is mainly because numerical computation required for the assessment is huge. The progress of computer hardware and software is solving this difficulty. In this section, we briefly mention a system, called *Integrated Earthquake Simulation* (IES)[4, 15, 16], which uses a set of numerical analysis methods for urban area earthquake disaster assessment, and present two examples of the numerical analysis methods which are put in the system.

4.1 Summary of IES

IES is aimed at providing a tool for urban area earthquake disaster assessment, by carrying out a series of numerical simulation. The target of the simulation is the three phases of earthquake disaster, namely, the ground motion generation, the urban area seismic response and the disaster reaction. For an urban area, analysis models are constructed for each phase, and distinct codes are used for physical or non-physical processes of the phases. It should be noted that output of one simulation of one phase is converted to input of another simulation of the next phase, so that the three phases will be seamlessly simulated for a given scenario of earthquake.

HPC is surely a core element of IES. Simulation of the three phases requires larger amount of numerical computation as more sophisticated codes and more detailed models are used; for instance, an analysis model of a building will eventually become the one shown in the preceding section. We should point out that, beside for the code and model, handling of input and output should be being improved in order to make larger and faster computation, by using most updated I/O hardware and software. At this moment, data generated in one phase reach 100 TB when a large urban area is simulated. IES is able to simulate various cases of earthquake disaster for one urban area, by considering many earthquake scenarios, which increases the data size of IES simulation.

In the following two subsections, we explain the urban area seismic response simulation and the mass evacuation simulation, for the phase of the urban area seismic response and the disaster reaction, respectively. The urban area seismic simulation uses an urban area model which consists of a set of building models and a non-linear seismic response code is applied to each of the building model. In the mass evacuation simulation, Multi Agent Simulation (MAS)[17, 18, 19, 20] is employed; agents are used as a model of human being who escapes in an urban area.

4.2 Urban Area Seismic Response Simulation

There have been developed numerous codes for non-linear seismic response simulation, which has sufficient accuracy, reliability and functionalities. The major task of the urban area seismic response simulation is not to develop a new code for the seismic structure response, but to construct an analysis model for each building, using available data so that we can take advantage of the existing codes. At this moment, Geographic Information System (GIS) which contain configuration data of buildings is available. We develop a code which automatically constructs an analysis model for one building, extracting necessary data from GIS and converting the data to the model.

A schematic view of the automatic construction is presented in Fig. 8. GIS which we are using has configuration data of different floors, and analysis models of different complexity are generated from one set of configuration data stored in GIS. Material properties as well as structure properties are *guessed* in constructing these analysis models. This is the limitation of the current module for the data construction.

There are some buildings which have quite complicated configurations in an urban area. It

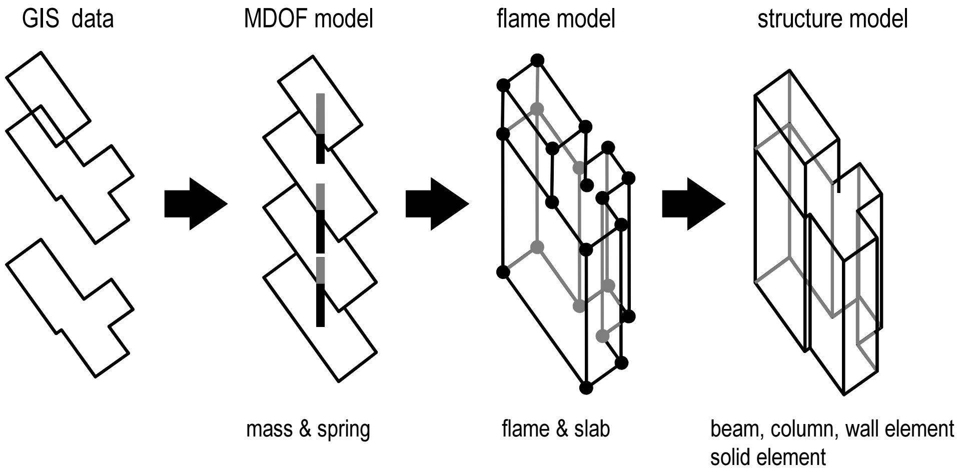


Figure 8: Construction of building model of different complexity from GIS data.

is not an easy task to make automated construction of an analysis model from the configuration data of such complicated building; in general, data stored in GIS are a set of point locations, and does not include information about connectivity. To deal with building with complicated configuration, we utilize a set of templates of floor arrangement. An analysis model is made from the template that best fits the building configuration. In Fig. 9, presented is the use of template sets to make a model for one building; the template is found by comparing the similarity in shape, and the model is constructed from the template. Some approximations are included in the process of constructing an analysis model from the template, not the structure configuration; for instance, the floor area cannot be computed exactly. However, the use of template set has high robustness in dealing with building of complex configuration, and the robustness is increased by adding new templates, which correspond to more complicated buildings.

As a typical example, we construct an urban area model of Tokyo Metropolis, for the urban area seismic response simulation. The non-linear one-component model is automatically constructed for around 2,000,000 buildings. We have to point out that the quality of the constructed models is not checked, since the number of the model is too large; we are planning to investigate natural frequencies of the generated model as the first step of checking the model quality. Seismic structure response is computed by analyzing each model for a given ground motion. This computation is so called *embarrassing parallel*, since it does not need inter-node communication. The parallel computation performance is highest, except for handling a large number of input and output data. Two snapshots of the urban area responses are presented in Fig. 10. The color legend is for the norm of displacement vector, and it is shown that higher buildings are shaken more than lower ones.

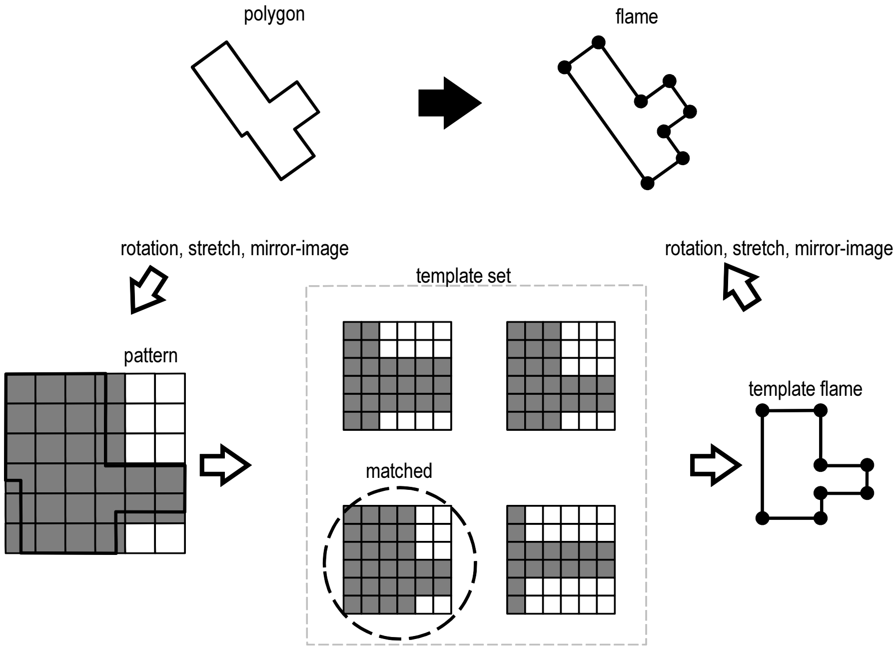


Figure 9: Use of template to make analysis model of building with complicated configuration.

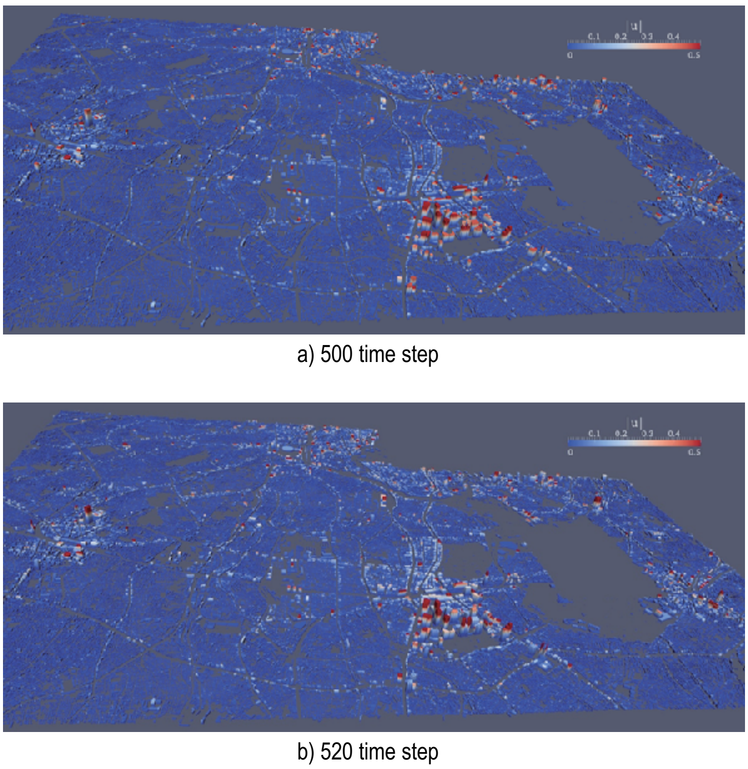


Figure 10: Snapshot of urban area seismic response of urban area model for Tokyo Metropolis.

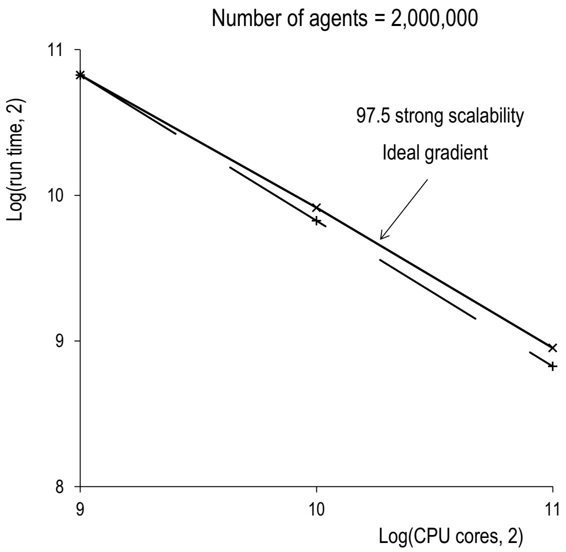


Figure 11: Parallel computation performance of MAS.

4.3 Mass Evacuation Simulation

As mentioned, IES employs MAS for the mass evacuation simulation[21], which, we think, is suitable to deal with situation in which *heterogeneous* persons escapes in a disorganized manner; the heterogeneity corresponds to the walking speed, the familiarity to the directory. An agent is designed to have `physical` and `intellectual` data, together with three functionalities of `seeing`, `thinking` and `moving`. It spontaneously moves in an evacuation route model interacting with the surrounding agents and finding the best route for the evacuation. In the mass evacuation simulation, a set of agents are generated in the evacuation route model, and the agents are activated to move towards pre-determined safe place or direction. The evacuation time, in which agents exit from the model, is an output of the simulation.

In Fig. 11, the parallel computation performance of MAS is plotted. While the number of the node is small, the performance of the code is satisfactory; it shows almost ideal strong scaling. Special cares are taken for the decomposition of analysis domain each of which is analyzed by one node. We should emphasize that since the code is written C++, which is not well supported by the current version of K computer system, the performance in the K computer environment is worse than the PC cluster environment; the use of C++ or other object oriented programing language is preferred in developing a code for MAS.

As a typical example of the output of the mass evacuation simulation, Fig. 12 shows snapshots of agents which move in the urban area model of evacuation routes; the model is constructed for Kochi City in Japan. Heterogeneous agents move smoothly, going from the top to the bottom of the figure. While overall movement of the agents is smooth, there are local conflicts created in the simulation. An agent stops or passes over other agents when it enters a crowded place. In very crowded situation, therefore, the current MAS produces less smooth movement of the agents.

While the primary objective of the mass evacuation simulation is more accurate assessment of earthquake disaster, it can be used for other purposes. As an example of such purpose, we consider the mass evacuation simulation in which *official* agents are introduced. The official agent seeks to find other agents which do not start evacuation and to make them do so. In view of 2011 Tohoku Earthquake, the importance of shortening preparation time for the tsunami

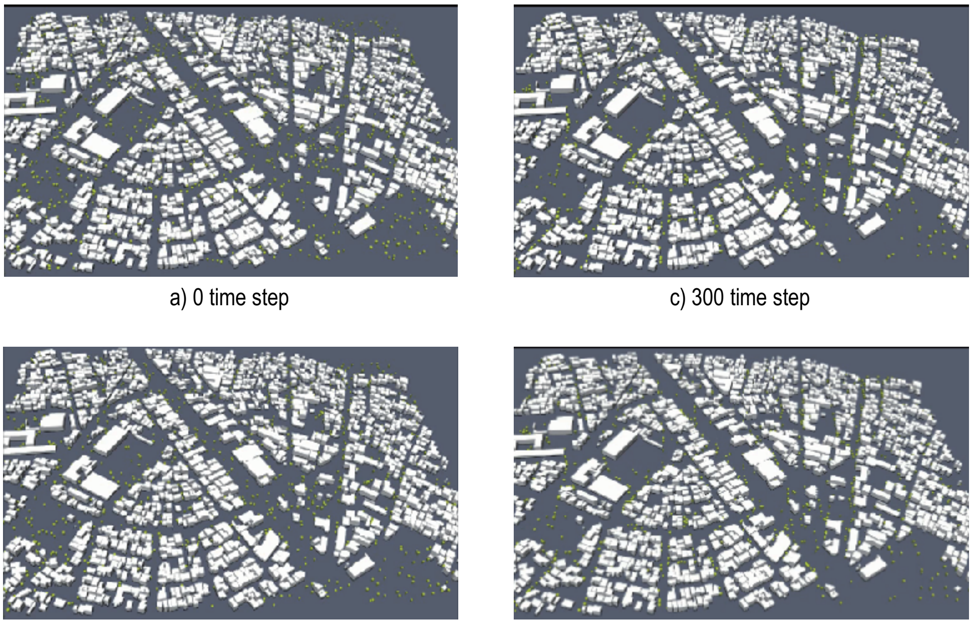


Figure 12: Snapshot of evacuating agents in mass evacuation simulation.

Table 4: Problem setting of official agent in mass evacuation simulation.

a) agent characteristics

Average moving speed [m/s]	1.4 (Normal) 1.1 (Slow)
S.D of moving speed [m/s]	0.6 (Normal) 0.3 (Slow)
Moving Speed of officials [m/s]	3.0
Average preparation time [s]	1000
S.D of preparation time [s]	240

b) setting of 5 cases

CASE	PET	OR (%)
1	No	-
2	Varying	0.0
3	Varying	0.5
4	Varying	1.0
5	Varying	3.0

PET Pre-Evacuation Time
OR Official Agent Ratio

evacuation is pointed out, and the official agent plays a role of an authority which guides residents. Snapshots of the official agents interacting other agents are presented in Fig. 13. It is shown that the official agents succeed to find agents which stop and make them move.

The mass evacuation simulation will give an answer to the question of "how many authorities are required in an urban area, in order to fasten tsunami evacuation." We study the reduction of the tsunami evacuation time by introducing the official agent. The problem setting is summarized in Table 4, and the results are shown in Fig. 14; the evacuation time for the ideal case (no preparation time) to the worst case (no authorities guiding evacuation) is plotted. As the ratio of the official agent increases, the evacuation time is decreased. However, the relation between the reduced time and the official agent ratio is not simple; it depends on the whole number of agents. The relation also depends on the complicatedness of the evacuation routes as well as the properties of the other agents. Many cases should be simulated in order to find a suitable ratio of the official agents.

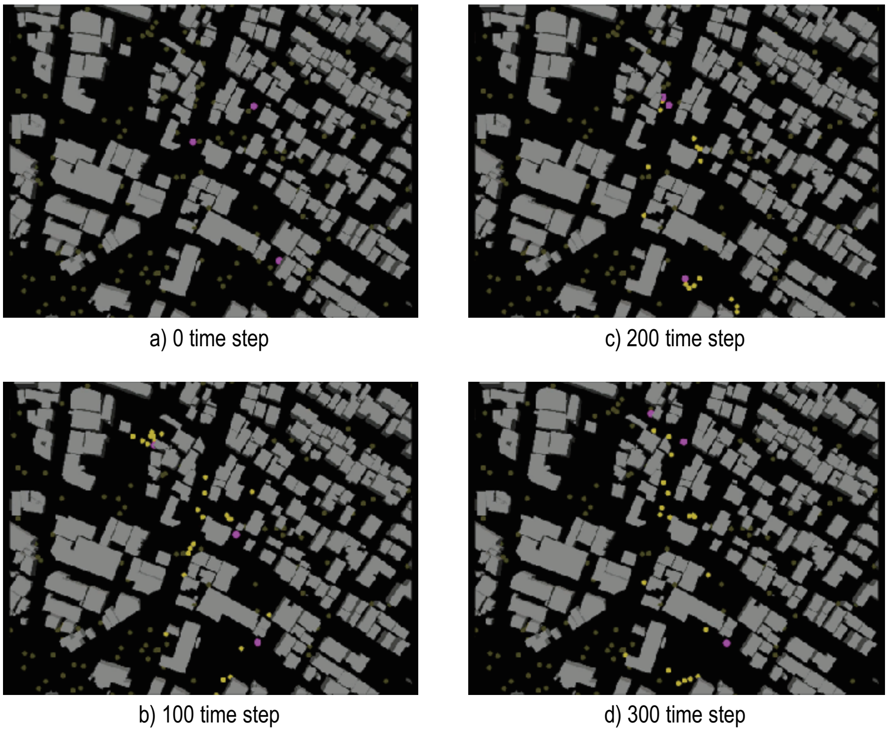


Figure 13: Snapshot of official agent guiding agents which do not start evacuation.

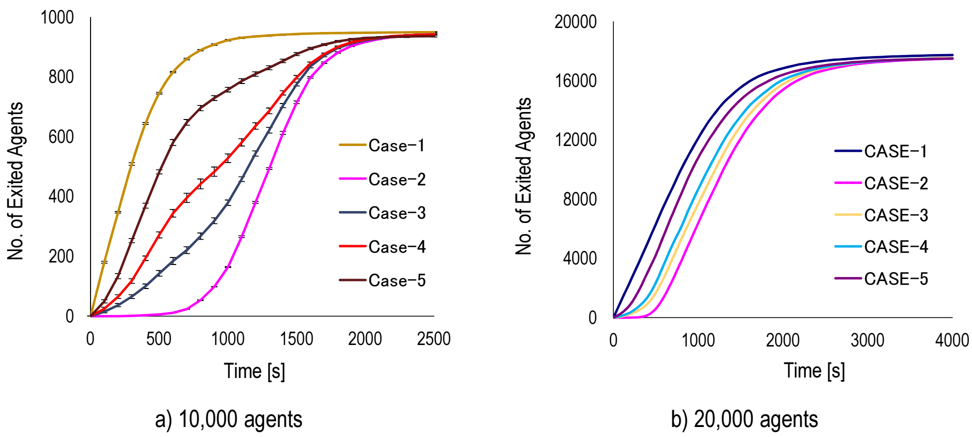


Figure 14: Evacuation time shortened by introducing official agent.

5 CONCLUDING REMARKS

This paper presents examples of applying HPC to two earthquake engineering problems, namely, the seismic structure response simulation and the urban area earthquake simulation. Strictly speaking, we are finishing code tuning that is required for the use of K computer; the validation of the computation results will be made when the tuning tasks are fully accomplished. Still, the results presented here show the potential advantage of applying HPC to solve the earthquake engineering problem.

Further development and improvement of the analysis codes is needed for the seismic structure response simulation and the urban area earthquake simulation. Beside for the code development, we need to construct a more reliable analysis model for a structure and an urban area. Although human efforts are inevitable to improve or correct the analysis model, most of tasks in constructing a model from a given set of data must be automated. We need to develop software for such model generation.

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