ASIAN JOURNAL OF CIVIL ENGINEERING (BUILDING AND HOUSING) VOL. 7, NO. 4 (2006)
PAGES 381-392

DEVELOPMENT OF INTEGRATED EARTHQUAKE SIMULATION FOR ESTIMATION OF STRONG GROUND MOTION, STRUCTURAL RESPONSES AND HUMAN ACTIONS IN URBAN AREAS

M. Hori*[1], T. Ichimura[2] and K. Oguni[1]
[1]Earthquake Research Institute, University of Tokyo, Tokyo, Japan
[2]Department of Civil Engineering, Tokyo Institute of Technology, Tokyo, Japan

ABSTRACT

Taking advantage of computer technology and science that enable us to carry out a large-scale numerical simulation, the authors have been simulating the whole phases of an earthquake, i.e., the generation and propagation of an earthquake, the response and damage of structures, and the human and society actions against the earthquake damages. This is the integrated earthquake simulation (IES). With the aid of the latest geographical information system (GIS), IES is able to automatically construct a compute model for a city of some hundred meter scale. This paper presents the development of IES, focusing the simulation of strong ground motion and structure responses; the structure response simulation is made by several numerical analysis methods and the data exchange between each method and IES is controlled by an interpreter program. Discussions are made on the usefulness of IES. It is pointed out that IES provides vital information to form common recognition of possible earthquake hazards and disasters among government officials and residents.

Keywords: earthquake simulation, structure response simulation, human action simulation

1. INTRODUCTION

Advanced numerical simulation is a candidate for predicting earthquake hazards and disasters, i.e., a possible distribution of strong ground motion and damages or collapses of structures which lead to loss of human lives and properties. The target of such numerical simulation is all phases of a possible earthquake, and it must achieve high spatial and temporal resolution to make a detailed prediction. Numerical simulation ought to provide further information; for instance, an estimation of variability in earthquake disasters due to different earthquake scenarios. Several research activities are carried out to develop a simulation system for the prediction and mitigation of earthquake hazards; for instance, see

* Email-address of the corresponding author: hori@eri.u-tokyo.ac.jp

[1, 2]; see also [3].

The authors are developing the macro-micro analysis method for the prediction of strong ground motion distribution when an earthquake scenario is given. The method achieves the prediction of high spatial and temporal resolution of strong ground motion distribution; it constructs two models for underground structures which are not fully identified and applies multi-scale analysis to increase the resolution of the simulation. Dynamic structural analysis methods which are developed for the purpose of earthquake resistant design are used for the prediction of damage to each structure.

This paper presents the current state of the integrated earthquake simulation (IES) that uses the macro-micro analysis method ant the dynamic structural analysis methods to predict possible earthquake hazards and disasters for a target urban area; see [4]. Computer models for buildings and structures in the area are automatically constructed by using a geographical information system (GIS); there are GIS's which store boring data from which an underground structure model is constructed. The contents of the paper are as follows: First, the macro-micro analysis method is briefly presented in Section 2. Second, the system of IES is presented with some explanation on the implementation of dynamic structure analysis methods in to IES in Section 3. Finally, an example of IES is shown in Section 4. Discussions are made for the usefulness of IES.

2. MACRO-MICRO ANALYSIS METHOD

For simplicity, it is assumed that the target underground structure, B, which includes geological structures and surface layers, is linearly elastic and isotropic and that Young's modulus E changes spatially but Poisson's ratio ν and density ρ are uniform. The distribution of E is not fully identified, and it is expressed as a stochastic random field; see [5, 6]. That is, E is a function of space $\boldsymbol{x}$ and a stochastic event ω, i.e., $E(\boldsymbol{x}, \omega)$; the argument ω stands for uncertainty of the value of E. When an incident wave is given to the boundary, the resulting wave that takes place in B varies stochastically, i.e., displacement u_i is a random vector field, $u_i(\boldsymbol{x}, \omega)$. The target of the macro-micro analysis method is to evaluate mean of u_i, i.e., $\langle u_i \rangle(\boldsymbol{x})$ with high spatial and temporal resolution; $\langle (.) \rangle$ stands for the probabilistic mean of (.).

The macro-micro analysis method is formulated by assuming a quasi-static state. When, say, displacement is prescribed on the boundary of B, a boundary value problem is posed for $u_i(\boldsymbol{x}, \omega)$. This problem is cast into the following stochastic variational problem:

$$J(u,c) = \iint_{B\times\Omega} \tfrac{1}{2} E(\boldsymbol{x},\omega)\, h_{ijkl}\, u_{i,j}(\boldsymbol{x},\omega)\, u_{k,l}(\boldsymbol{x},\omega)\, dv_{\boldsymbol{x}}\, P(d\omega), \tag{1}$$

where

$$h_{ijkl} = \frac{\nu}{(1+\nu)(1-2\nu)}\delta_{ij}\delta_{kl} + \frac{1}{2(1+\nu)} I_{ijkl} \tag{2}$$

with δ_{ij} and I_{ijkl} being Kronecker's delta and the forth-order symmetric identity tensor; Ω is a stochastic space and $P(d\omega)$ is a stochastic measure; an index following a comma stands for the partial differentiation. The stochastic functional J is minimized for the exact stochastic displacement, and, by definition, the minimum value is the mean of the strain energy stored in B, denoted by <E>. It is of interest to note that when a non-stochastic (or deterministic) u_i is put into J, the integration with respect to ω applies only to E, and hence the following inequality holds:

$$<\mathsf{E}> \; < \; \int_B \tfrac{1}{2} < \mathrm{E} >(\boldsymbol{x}) \; \mathrm{h}_{ijkl} \; \mathrm{u}_{i,j}(\boldsymbol{x}) \, \mathrm{u}_{k,l}(\boldsymbol{x}) \, \mathrm{dv}_{\boldsymbol{x}}, \tag{3}$$

Thus, displacement function for a fictitious but deterministic body with Young's modulus $<E>(\boldsymbol{x})$ provides an upper bound for <E>. Similarly, it is shown that displacement function for a body with 1/<1/E> provides a lower bound. The macro-micro analysis method thus uses these two bodies for a stochastic body B.

The macro-micro analysis method solves a wave equation for the body with $<E>$ (or $1/<1/E>$). The difficulty arises since the spatial change in $<E>$ is abrupt and not small. The singular perturbation expansion that leads to a multi-scale analysis is employed in solving the wave equation. For simplicity, the wave equation is written in the following manner:

$$\mathrm{d}_i(\mathrm{c}_{ijkl}(\boldsymbol{x})\mathrm{d}_l\mathrm{u}_k(\boldsymbol{x},\mathrm{t})) - \rho\ddot{\mathrm{u}}_j(\boldsymbol{x},\mathrm{t}) = 0, \tag{4}$$

where $c_{ijkl} = <E>h_{ijkl}$ and $\mathrm{d}_i = \partial/\partial \mathrm{x}_i$. Since Young's modulus changes in a much smaller length scale than the size of B, a small parameter ε is introduced such that a spatially fast varying $\boldsymbol{x} = \boldsymbol{X}/\varepsilon$ is defined. The singular perturbation expansion is carried out by replacing d_i with $d_i + D_i/\varepsilon$ with $\mathrm{D}_i = \partial/\partial \mathrm{X}_i$ and expanding u_i as $\mathrm{u}_i^{(0)} + \varepsilon \mathrm{u}_i^{(1)}$; the second term, $\varepsilon \mathrm{u}_i^{(1)}$, is the correction that accompanies strain of the order of ε^0 even though its amplitude is of the order of ε^1. After some manipulation, Eq. (4) leads to the governing equation for $\mathrm{u}_i^{(0)}$ and $\mathrm{u}_i^{(1)}$, as

$$\begin{cases} D_i(\bar{c}_{ijkl}(\boldsymbol{X})D_l u_k^{(0)}(\boldsymbol{X},t)) - \rho\ddot{u}_j^{(0)}(\boldsymbol{X},t) = 0, \\ d_i(c_{ijkl}(\boldsymbol{x})(D_l u_k^{(0)}(\boldsymbol{X},t) + d_l u_k^{(1)}(\boldsymbol{x},t))) - \rho\ddot{u}_j^{(1)}(\boldsymbol{x},t) = 0, \end{cases} \tag{5}$$

where $\bar{c}_{ijkl}$ is the local average of elasticity that is defined as

$$\bar{\mathrm{c}}_{ijkl}\mathrm{D}_l\mathrm{u}_k^{(0)} = 1/\mathrm{b}\int_b \mathrm{c}_{ijkl}(\mathrm{D}_l\mathrm{u}_k^{(0)} + \mathrm{d}_l\mathrm{u}_k^{(1)})\mathrm{dv} \tag{6}$$

with b being a small region near a point $\boldsymbol{X}$; $\mathrm{u}_i^{(1)}$ is given as $\mathrm{u}_i^{(1)}(\boldsymbol{X},\boldsymbol{x},\mathrm{t})$ in b and regarded as a function linear to $\mathrm{u}_i^{(0)}(\boldsymbol{X},\mathrm{t})$ while $\mathrm{u}_i^{(0)}$ is given as a function independent from $\boldsymbol{x}$, i.e., $\mathrm{u}_i^{(0)}(\boldsymbol{X},\mathrm{t})$. Equation (5) is the target of the macro-micro analysis method. It should be emphasized that the spatial resolution determines the temporal resolution in solving the wave equation. Some extrapolation is needed to relate $u_i^{(0)}$, which is computed in coarser discretization, to $u_i^{(1)}$, which is computed in finer discretization. Figure 1 presents the schematic view of the macro-micro analysis method which constructs two deterministic models for uncertain ground structures and solves wave equations using the multi-scale analysis based on the singular perturbation expansion.

Ichimura and Hori [7,8] show that the macro-micro analysis method is able to reproduce measured records of strong ground motion to some extent. They study two earthquakes in Japan and compare the records and the synthesized waves at 13 sites which are located in Yokohama City. The target area is 100×200×60[km]. In a frequency domain, the synthesized wave is computed up to 5[Hz], which is the finest resolution of the numerical simulation. Some differences can be seen in the wave forms. However, for some engineering indexes such as seismic index or peak ground velocity, the simulation results of the macro-micro analysis method are in good agreement with the observed values.

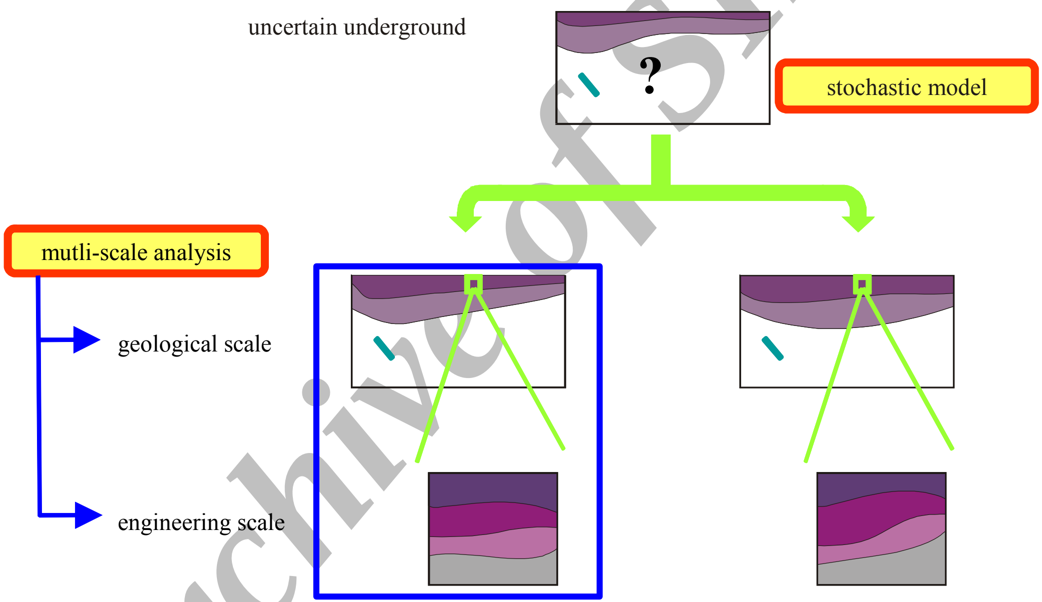


Figure 1. Schematic view of macro-micro analysis method

3. IES (INTEGRATED EARTHQUAKE SIMULATION)

As briefly mentioned in Section 1, IES is a simulation system for the following three phases of an earthquake: 1) generation and propagation of an earthquake wave; 2) response and damage of structures subjected to strong ground motion; and 3) human and social actions against earthquake disasters. The overview of IES is presented in Figure 2; see [6]. While each simulation has its own purpose, the three simulations are related to each other, i.e., the earthquake simulation provides strong ground motion distribution to the structure response simulation; for each building, the strong ground motion at its site is used as an input wave. Structure damage which is computed by the structure response simulation provides an initial condition for the action simulation.

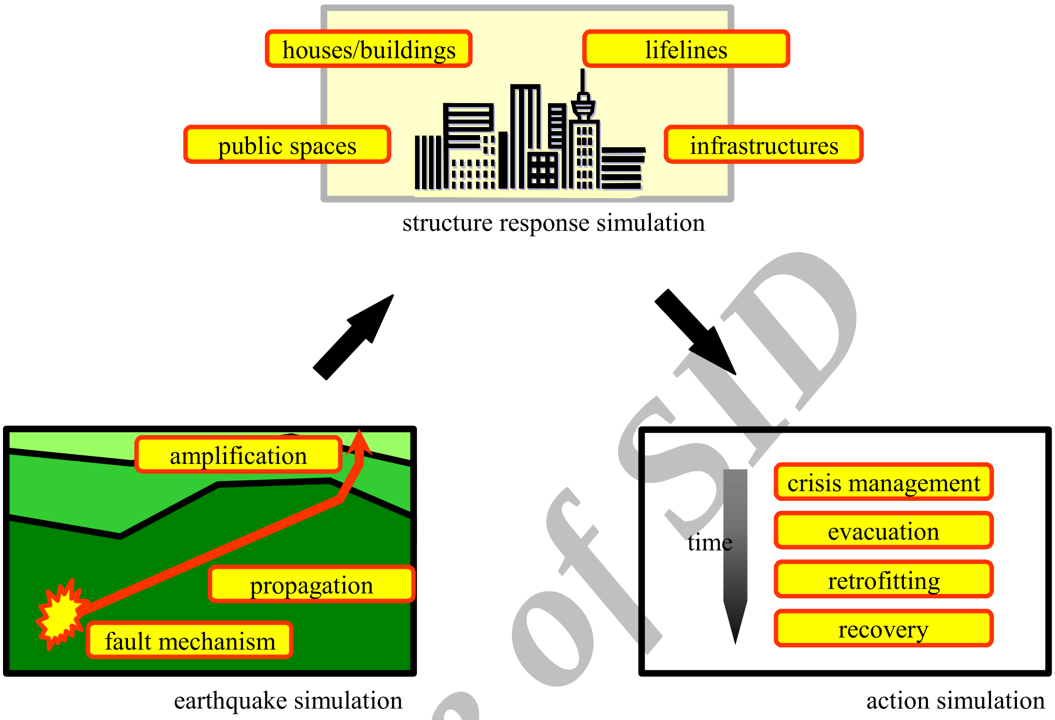


Figure 2. Overview of IES

IES consists of GIS and the three groups of numerical simulations. GIS provides data to construct computer models, i.e., underground structure data for the earthquake simulation and structure data for the structure response simulation. Results of the numerical simulation are stored in GIS. As shown in Figure 3, a kernel of IES is the key element of IES, since it controls IES itself. It is the kernel that actually communicates with GIS and executes simulation programs providing data and receiving results, and transforms the simulation results in a form which is applicable to various visualization tools. The visualization tools generate three-dimensional static images or animations.

For the structure response simulation, IES makes use of an interpreter program, called a mediator, in order to analyze various buildings and structures; see, for instance, [9-11] for the concept of the mediator. Each type of a structure has its own dynamic response characteristics and hence a particular structural analysis is needed. The mediator puts suitable input data into a program of the structural analysis for execution, and takes simulation results for the unified visualization. In making the input data, a suitable computer model is made for each structure by using data stored in GIS, and the simulation results are transformed to a common format so that the visualization tools of IES can work. Due to the use of mediators, IES is similar to a federation-type data base which connects independent data base to each other by using some interpreter programs which exchange data stored in different data bases; see Figure 4.

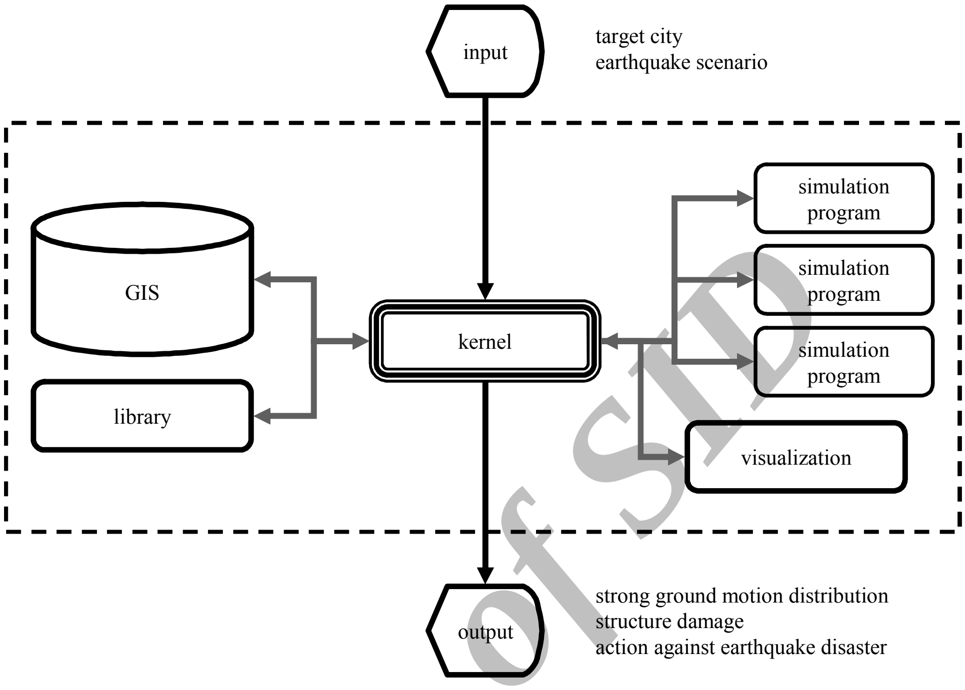


Figure 3. Structure of IES

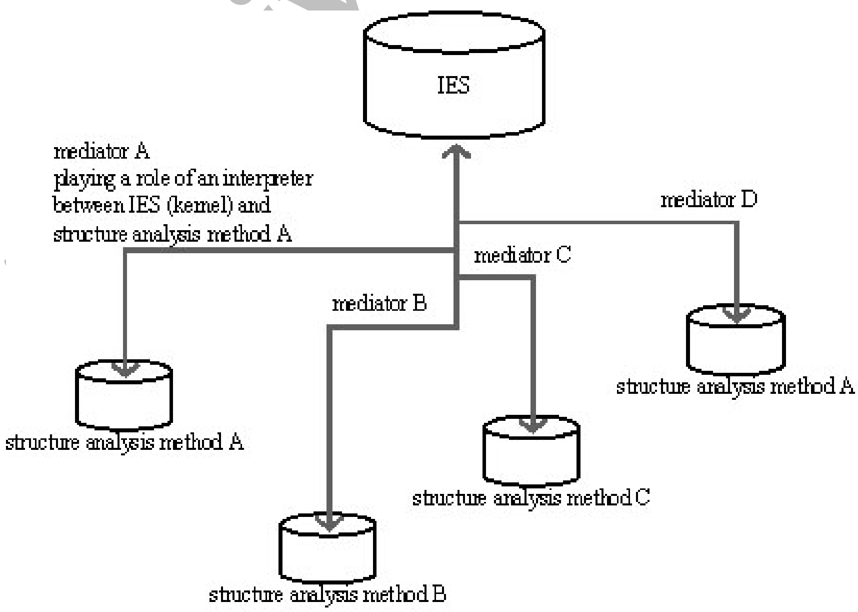


Figure 4. Mediators of IES

The mediator is made as an object, and its program structure are designed by considering functions that are required to translate the kernel and each structural analysis method. Furthermore, an artificial intelligence program, called a mediator maker, is being developed so that a mediator is automatically made for a given structure analysis method. Most of structure analysis methods are based on a finite element method, and have a more or less common program structure. Thus, it is possible to automatically construct a mediator. At this moment, however, the mediator maker is not robust and often fails to make a mediator. The current mediator maker is able to extract input and output commands from a given source code by considering conditions and loops, which helps write a mediator program by hand.

4. EXAMPLE OF IES

With the aid of the mediators which are produced by the mediator maker, IES constructs a virtual city (VC) as a computer model for an artificial city of 300x300[m] area; see [11] for a computer model of city; see also [12]. A small GIS is used for this city; GIS stores data enough to construct computer models for the underground structure and the man-made structures. The underground structure is up to depth of 40[m], and consists of three distinct layers. There are four gas pipe lines, five concrete piers, seven steel piers of two kinds and four ground molds. A schematic view of VC is presented in Figure 5. This Figure is a result of visualization; one visualization tool of IES automatically generates the static image of VC, while other tools generates dynamic images (animation) of VC as well as static and dynamic images for each structure within VC.

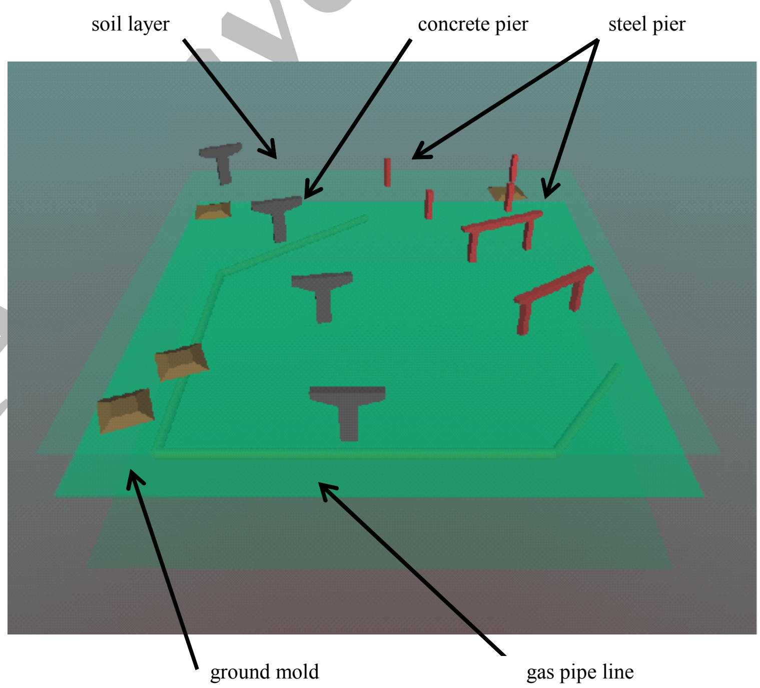


Figure 5. Bird view of VC

It should be emphasized that constructing a mediator is not trivial, due to the difficulty in presuming variable. A mediator maker seeks to find some variables which are commonly used in structural analysis methods based on a finite element method, namely, the node number, the element number and the time increment number. These variables are input in the beginning of the input part and used in the loop part, and the mediator maker seeks to find them as follows:

1) the node number as a variable which controls the iteration of the input part and of the output subpart;
2) the element number as a variable which controls the iteration of the output subpart;
3) the time increment number as a variables which control the iteration of the loop part.

The mediator maker analyzes all variables in a given source code and examines the frequency of appearance for them. As an example, a source code of an analysis method of concrete pier is analyzed, and the frequency of appearance is shown in Figure 6; read/write means input/output, and LL means the loop level (LL=0 or =1 is out of loop sentences or in the first nest of loop sentences). As is seen, variables INODE, IMEM, IJK are presumed as the node number, the element number and the time increment number, which is correct presumption.

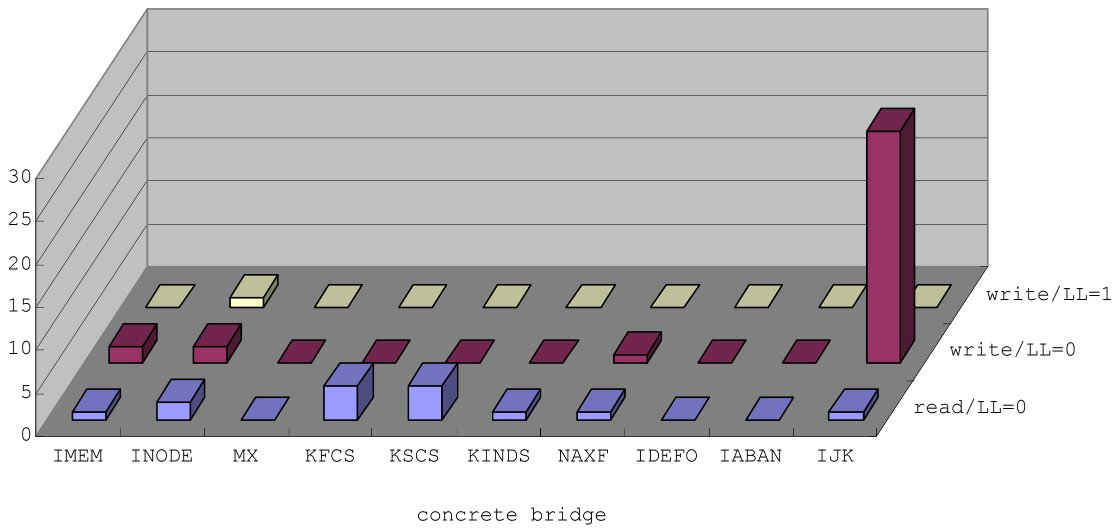


Figure 6. Results of mediator maker analysis in presuming variables used in a source code

Examples of the visualization of VC are shown in Figure 7; a half sinusoidal wave of amplitude 10[cm] and period 1.0[sec] is input at the bedrock mass, and Figures are snapshots of bird-views of VC every 0.2[sec]. The displacement of structures is magnified by 10 times, and the norm is indicated by color. As expected, structures of the identical configuration and material properties have different responses since strong ground motion input to them is not the same due to the difference in local ground structures, which results in different amplification of earthquake; see ground molds. Structures of different kinds have responses which are mainly governed by the natural frequency; for instance, concrete and steel piers located at the center of VC have large contrast in amplitude of displacement, and the maximum displacement of the concrete pier is just 20% of that of the steel pier.

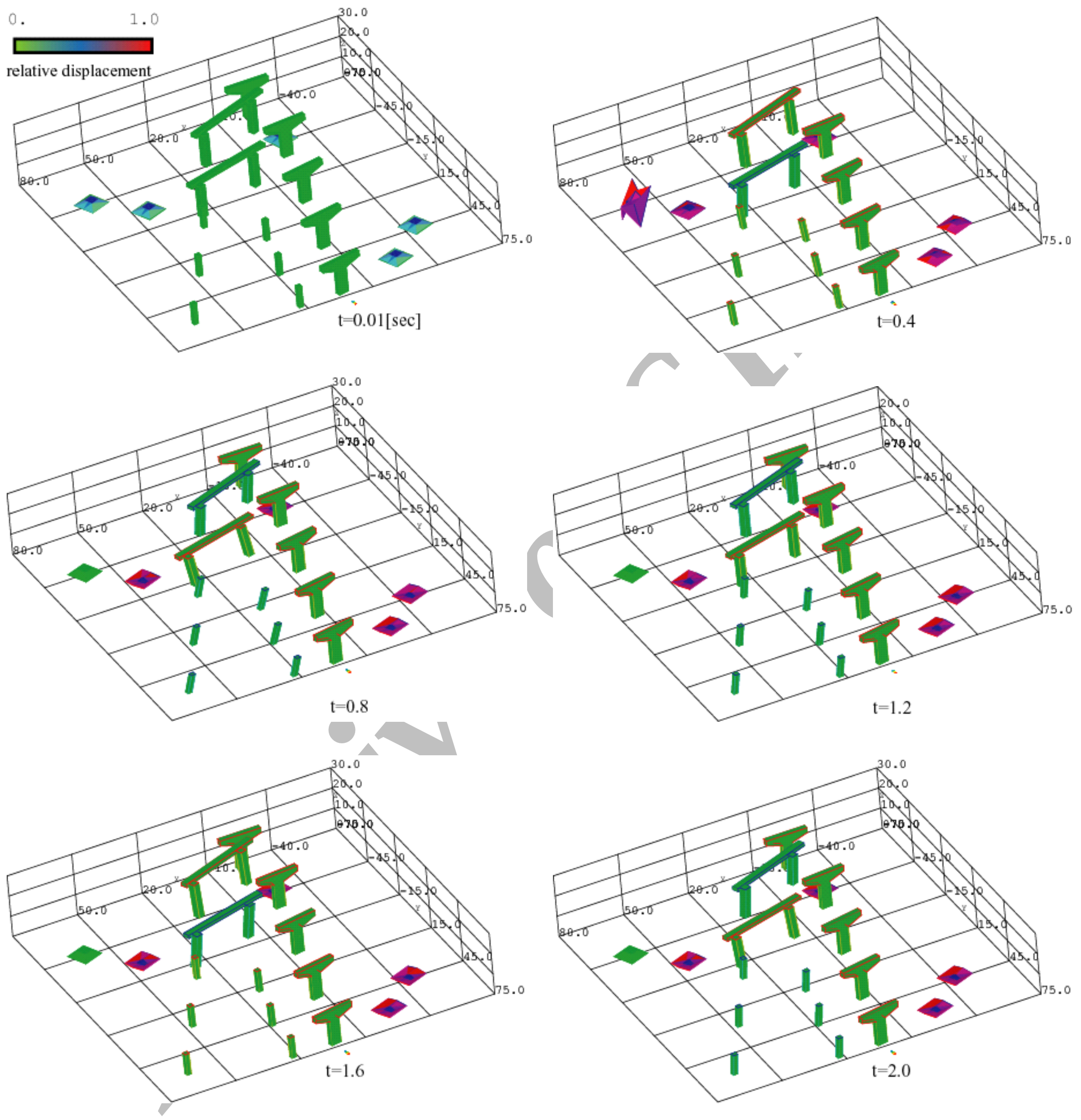
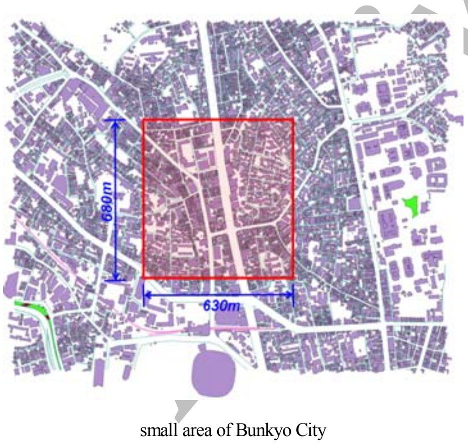


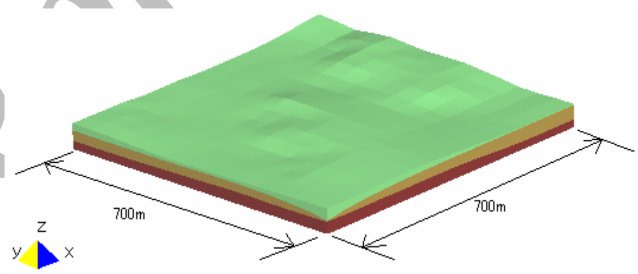
Figure 7. Dynamic images of VC

It should be emphasized that structural analysis methods implemented into IES have been used to analyze dynamic non-linear responses of a structure for the research purpose. Thus, the reliability of the simulation is high. The visualization of earthquake disasters which are predicted by such simulation contributes to the improvement of the engineering ability of local government officials who are in charge of promoting earthquake disaster mitigation, since it provides a vivid image of the disasters. While more realistic visualization will be needed, the visualization of quantitative information of the structure damages in making more efficient mitigation plans. Furthermore, the visualization can contribute to make a common recognition of earthquake hazards and disasters among residents as well. Such common recognition is a key in enforcing the mitigation plans. IES provides different predictions of earthquake hazards and disasters depending on an earthquake scenario. The visualization of these predictions helps the local government officials and the residents understand a possible range of earthquake damages. It is important to tell them the predictions that are based on the latest scientific knowledge and the most advanced technology; the officials and residents are able to choose the most reasonable preparation for a possible earthquake, considering other factors such as financial situations.

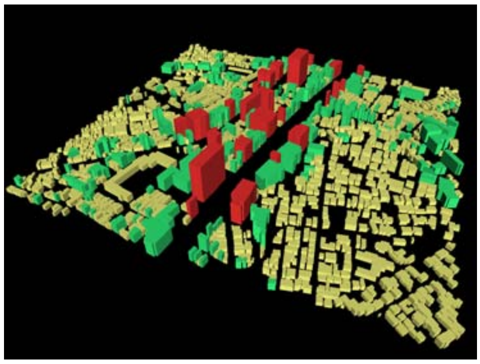
The results presented above are made by a prototype of IES. A more advanced IES is being constructed so that it can cope with a commercially available GIS which covers most of major cities in Japan. The basic structure and function are the same; only interfaces between the kernel and GIS are updated. An example of this IES is shown in Figure 8: the model is made for a small area of 500x500[m] in Bunkyo City, Tokyo. Computer models are automatically made for the underground structures and several hundred buildings. The results of the earthquake simulation and the structure response simulation are shown in Figure 9.



small area of Bunkyo City



underground structure model; three distinct layers up to depth of 40[m]



building models; red, green and yellow are for high, middle and low residential houses and buildings

Figure 8. A small area of Bunkyo City and its computer model for IES

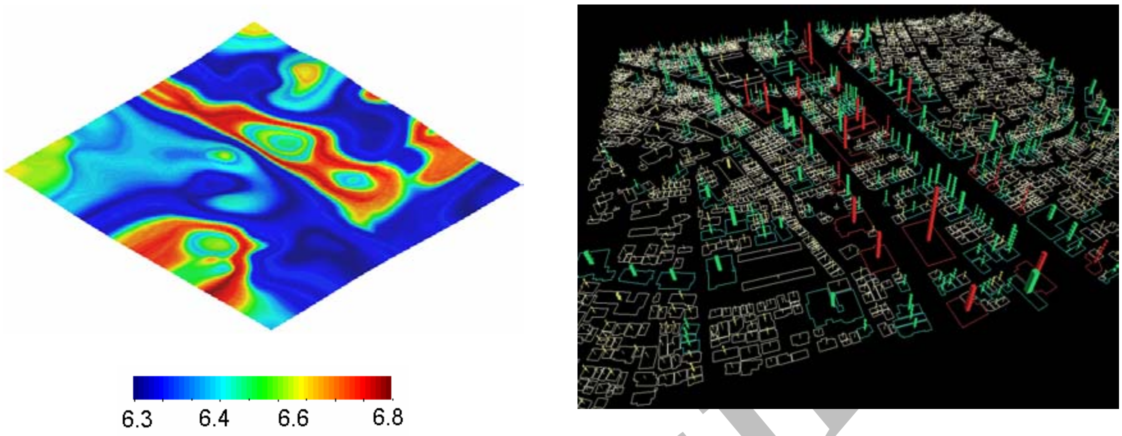


Figure 9. Results of IES for Bunkyo City model

5. CONCLUDING REMARKS

IES is being developed to deliver local government officials and residents quantitative information about possible earthquake hazards and disasters which are obtained by means of large-scale simulation of all earthquake phases for a given earthquake scenario. The visualization of the simulation results is a key element of IES. However, the reliability of the simulation results should not be underestimated. For instance, the earthquake simulation employs the macro-micro analysis method, and it is necessary to improve the method so that more accurate prediction with higher resolution can be achieved. Also, a larger-scale of simulation is needed for IES to be applied to a larger area.

REFERENCES

1. Kitano, H. Tadokoro, S., Noda, I., Matsubara, H., Takahashi, T., Shinjoh, A. and Shimada, S., RoboCup Rescue: search and rescue in large-scale disasters as a domain for autonomous agent research, *Proc. 1999 IEEE Intl. Conf. on Systems, Man and Cybernetics*, **VI**, *Tokyo* (SMC 99), 1999, pp. 739-743.
2. Tadokoro, S., Takamori, T., Osuka, K. and Tsurutani, S., Investigation report of the Rescue Problem at Hanshin-Awaji Earthquake in Kobe, *Proceedings of 2000 IEEE/RSJ, International Conference on Intelligent Systems and Robots* (IROS 2000), 2000.
3. NIED-EDM Kawasaki Laboratory, *Research result report on development of comprehensive simulation system for earthquake disaster*, National Research Institute for Earth Science and Disaster Prevention (NIED) (in Japanese), 2005, Tokyo.
4. Hori, M., *Introduction to computational earthquake engineering*, Imperial College

Press (in print), 2006, London.

5. Ichimura, T., and Hori, M., Macro-micro analysis method for strong motion distribution," *J. Struct. Eng./Earthquake Eng.*, JSCE, **I-52**, **654**, 2000, pp. 51-62.
6. Hori, M. Ichimura, T. and Nakagawa. H., Analysis of stochastic model: application to strong motion and fault problems, *J. Struct. Eng./Earthquake Eng.*, JSCE, **I-20/2** (2003) 11-24.
7. Ichimura, T. and Hori, M., Macro-micro analysis method for wave propagation in stochastic media, *Earthquake Engineering & Structural Dynamics* (in press), 2006.
8. Ichimura, T. and Hori, M., Strong ground motion prediction using macro-micro analysis method, *Earthquake Engineering & Structural Dynamics* (in press), 2006.
9. Gruber, T. R., A translation approach to portable ontology specification, *Knowledge Acquisition*, No. 2, **5**(1993) 199-220.
10. Hammer, J., Gracia-Monlina, H., Ireland, K., Papakonstantinou, Y., Uhlman, J. D. and Widom, J., Information translation, mediation, and mosaic-based browsing in the TSIMMIS system, *Exhibits Program of the Proceedings of the ACM SIGMOD International conference on Management of Data*, 1995, pp. 483.
11. Hirose, M., Tanikawa, T. and Endo, T., Building a virtual world from the real world, *Mixed Reality-Merging Real and Virtual Worlds* (ed. by Ohta, Y and Tamura, H.), Springer-Verlag, 1999, pp. 183-197.
12. Yang, F., Ichimura, T. and Hori, M., Earthquake simulation in virtual metropolis using strong motion simulator and geographic information system, *Journal of Applied Mechanics*, JSCE, **5**(2002) 527-534.