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Integrated Earthquake Simulation—Estimation of Strong Ground Motions and Structural Response

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Abstract

Advances in computer technology and sciences enable us to carry out large-scale numerical simulations. As one of such, the authors have been simulating the entire process of an earthquake, i.e., generation and propagation of an earthquake, responses of structures and damage, and actions by people and communities for earthquake damage. This is an integrated earthquake simulation (IES). With the aid of the latest geographical information system (GIS), IES can automatically construct a computer model of a city of some hundred meters in scale. This paper presents the current state of IES, focusing on the simulation of strong ground motions and structure responses ; the structure response simulation applies several numerical analysis methods. Data exchanges between each method and IES are controlled by an interpreter program. The usefulness of IES is discussed. It is pointed out that IES provides vital information to form a common recognition of possible earthquake hazards and disasters by government officials and residents.

Key words : integrated earthquake simulation, geographical information system, strong ground motion simulation, structural response simulation

1. Introduction

Advanced numerical simulation is a candidate tool for predicting earthquake hazards and disasters, i.e., possible distribution of strong ground motions and damage or collapse of structures that lead to loss of life and property damage. The targets of such a numerical simulation are all phases of a possible earthquake, and it must achieve high spatial and temporal resolution to make a detailed prediction. A 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 predicting and mitigating earthquake hazards ; for instance, see Kitaono *et al.* (1999) and Tadokoro *et al.* (2000) ; see also NIED Kawasaki Laboratory (2005).

The authors are developing a macro-micro analysis method for predicting strong ground motion distribution when an earthquake scenario is given. Prediction with high spatial and temporal resolution of strong ground motion distribution has achieved, and a macro-micro analysis method constructs two models of underground structures that are not fully identified, and applies a multi-scale analysis to increase the spatial resolution of the simulation. Dynamic structural analysis methods that are developed for earthquake resistant designs are used for predicting damage to each structure.

This paper presents the current state of the integrated earthquake simulation (IES) that uses the macro-micro analysis method and dynamic structural analysis methods to predict possible earthquake hazards and disasters for a target area ; see Hori (2006). Computer models of buildings and structures in the area are automatically constructed using a geographical information system (GIS). Some GIS 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

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briefly presented in Section 2. Second, the IES system is presented with some explanation of the implementation of dynamic structure analysis methods in IES in Section 3. Finally, an example of an IES is shown in Section 4. Some discussions are presented on 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 in B. The distribution of E is not fully identified, and is expressed as a stochastic random field ; see Ichimura and Hori (2000) and Hori *et al.* (2003). That is, E is a function of space x and a stochastic event ω, i.e., $E(x,\omega)$; the argument ω stands for the uncertainty of the value of E. When an incident wave is given to the boundary, the resulting wave that occurs in B varies stochastically, i.e., displacement u_i is a random vector field, $u_i\ (x,\omega)$. The target of the macro-micro analysis method is to evaluate mean of u_i, i.e., $<u_i>(x)$ with a high spatial and temporal resolution ; $<(.)>$ stands for the probabilistic mean of (.).

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

$$J(u,c)=\int\int_{B\times\Omega}\frac{1}{2}E(x,\omega)h_{ijkl}u_{i,j}(x,\omega)u_{kl}(x,\omega)\,d\nu_x P(d\omega), \quad (1)$$

where

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

with δ_{ij} and $Iijkl$ 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, integration with respect to ω applies only to E, hence the following inequality holds :

$$<E><\int_B\frac{1}{2}<E>>(x)h_{ijkl}u_{i,j}(x)u_{k,l}(x)d\nu_x, \quad (2)$$

Thus, the displacement function for a fictitious but deterministic body with Young's modulus$<E>(x)$ provides an upper boundary for$<$E$>$. Similarly, it is shown that the displacement function for a body with 1/$<$1/E$>$ provides a lower boundary. 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 a body with$<E>(x)$ (or $1/<1/E>(x)$). The difficulty arises because the spatial change in$<E>(x)$ is abrupt and not small. The singular perturbation expansion that leads to a multi-scale analysis is employed for solving the wave equation. For simplicity, the wave equation is written in the following manner :

$$d_i(c_{ijkl}(x)d_l u_k(x,t))-\rho\ddot{u}_j(x,t)=0, \quad (3)$$

where $c_{ijkl}=<E>h_{ijkl}$ and $d_i=\partial/\partial x_i$. Because Young's modulus changes in a much smaller length scale than the size of B, the small parameter ε is introduced such that a spatially fast varying $x=X/\varepsilon$ is defined. The singular perturbation expansion is carried out by replacing d_i with d_i+D_i/ε with $D_i=\partial/\partial X_i$ and expanding u_i as $u_i^{(0)}$; the second term,$u_i^{(1)}$, is a 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. (3) leads to the governing equation for $u_i^{(0)}$ and $u_i^{(1)}$, as

$$\begin{aligned}&D_i(\bar{c}_{ijkl}(X)D_l u_k^{(0)}(X,t))-\rho\ddot{u}_j^{(0)}(X,t)=0,\\&d_i(c_{ijkl}(x)(D_l u_k^{(0)}(X,t)+d_l u_k^{(1)}(x,t)))\\&\quad-\rho\ddot{u}_j^{(1)}(x,t)=0,\end{aligned} \quad (4)$$

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

$$\bar{c}_{ijkl}D_l u_k^{(0)}=1/b\int_b c_{ijkl}(D_l u_k^{(0)}+d_i u_k^{(1)})d\nu$$

with b being a small region near point X ; $u_i^{(1)}$ is given as$u_i^{(1)}(X,x,t)$ in b and is regarded as a function linear to $u_i^{(0)}(X,t)$ while $u_i^{(0)}$ is given as a function independent from x, i.e., $u_i^{(0)}$(X, t). Equation (4) is the target of the macro-micro analysis method. It should be emphasized that spatial resolution determines temporal resolution when 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 com-

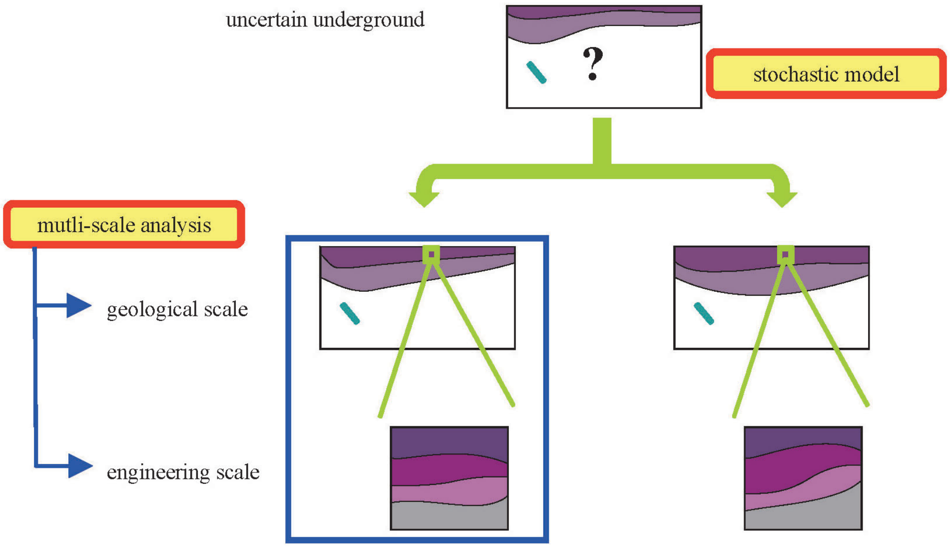


Fig. 1. Schematic view of macro-micro analysis method ; a stochastic model is made for an uncertain ground structure, and two deterministic models are made so that the mean behavior of the stochastic model is estimated by the solution obtained by applying the multi-scale analysis.

puted in finer discretization. Figure 1 presents a schematic view of the macro-micro analysis method that 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 (2006a, b) show that the macro-micro analysis method can reproduce measured records of strong ground motions to some extent. They studied two earthquakes in Japan and compared the records and the synthesized waves at 13 sites located in Yokohama City. The target area was 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.

3. IES

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 of structures subjected to strong ground motion and damage to them ; and, 3) human or social actions against earthquake disasters. An overview of IES is presented in Fig. 2 ; see Hori (2006). While each simulation has its own purpose, the three simulations are related to each other ; i.e., the earthquake simulation provides a strong ground motion distribution for the structure response simulation ; for each building, the strong ground motion at its site is used as an input wave. Structural damage computed by the structure response simulation provides the initial condition for the action simulation.

IES consists of GIS and 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 Fig. 3, the kernel of IES is the key element of IES, because it controls the 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 into a form to which various visualization tools can be applied. 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, to analyze various buildings and structures ; see, for instance, Gruber (1993) and Hammer *et al.* (1995) and

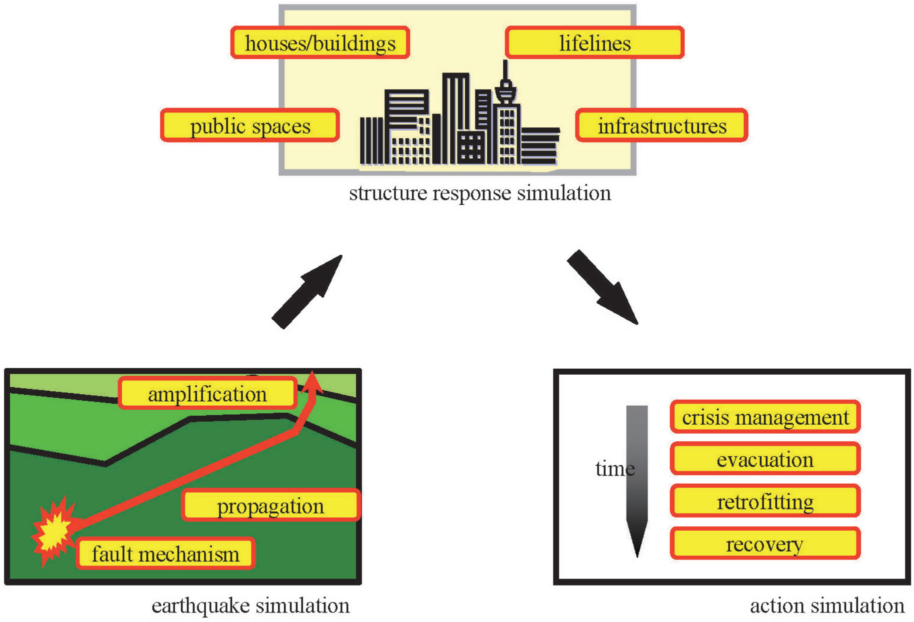


Fig. 2. Overview of IES.

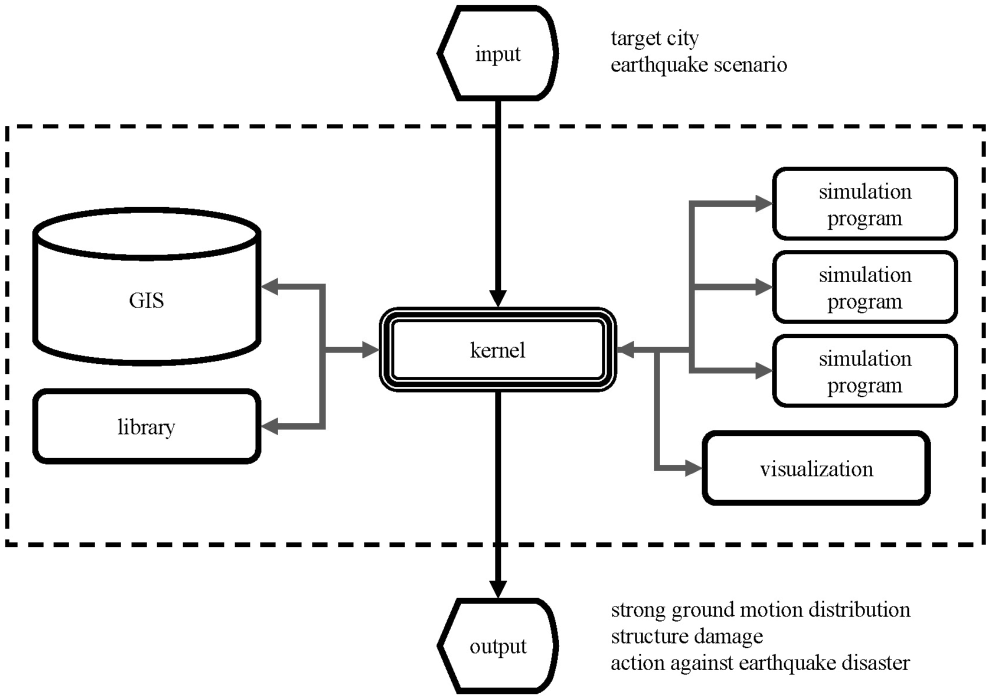


Fig. 3. Structure of IES ; a kernel controls the IES itself.

Hirose *et al.* (1999) for the concept of the mediator. Each type of 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. When preparing the input data, a suitable computer model is built for each structure using data stored in GIS, and the simulation results are transformed to a common format so that the visualization tools of IES can be applied. Due to the use of mediators, IES is similar to a federation-type database that connects independent databases to each other using some interpreter programs that exchange data stored in different databases ; see Fig. 4.

The mediator is made the object, and its program structure is designed by considering the 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 structural analysis method. Most structural 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 present, 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 produced by the mediator maker, IES constructs a virtual city (VC) as a computer model for an artificial city of 300×300 [m] area ; see Hirose *et al.* (1999) for a computer model of a city ; see also Yang *et al.* (2002). A small GIS is used for this city ; GIS stores enough data to construct computer models of underground locations and structures. The underground structure has a depth of up to 40 [m], and consists of three distinct layers. There are four gas pipelines, five concrete piers, seven steel piers of two types, and four ground molds. A schematic view of VC is presented in Fig 5. This figure is the result of a visualization ; one visualization tool of IES automatically generates a static image of VC, while other tools generate dynamic images (animation) of VC as well as static and dynamic images of each structure within VC.

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

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

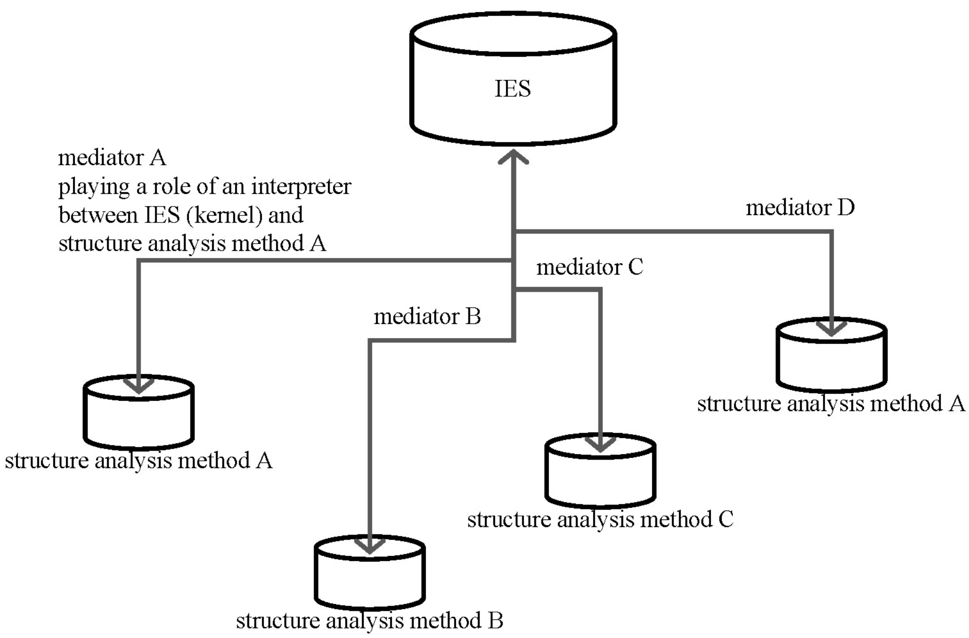


Fig. 4. Mediators of IES ; a mediator plays a role of an interpreter between the IES kernel and a structural analysis method when exchanging data and simulation results.

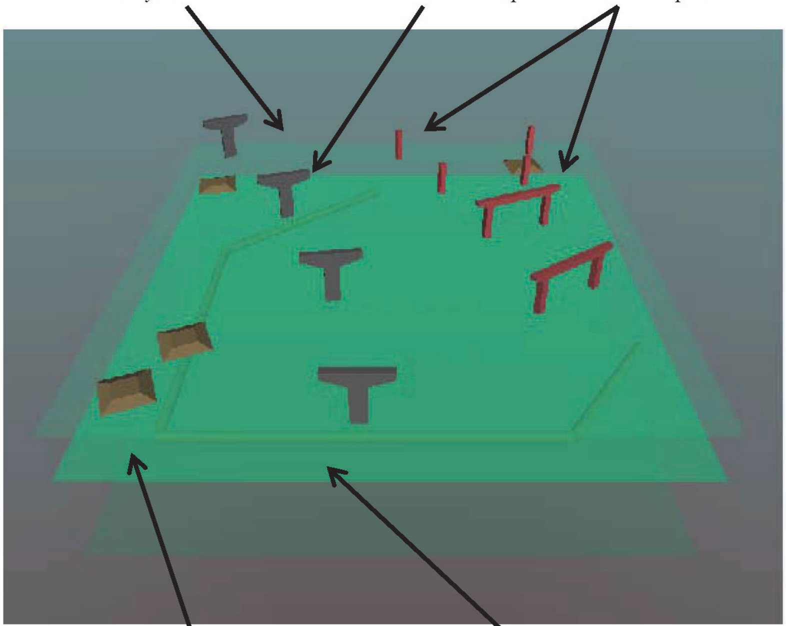


Fig. 5. A bird's eye view of VC.

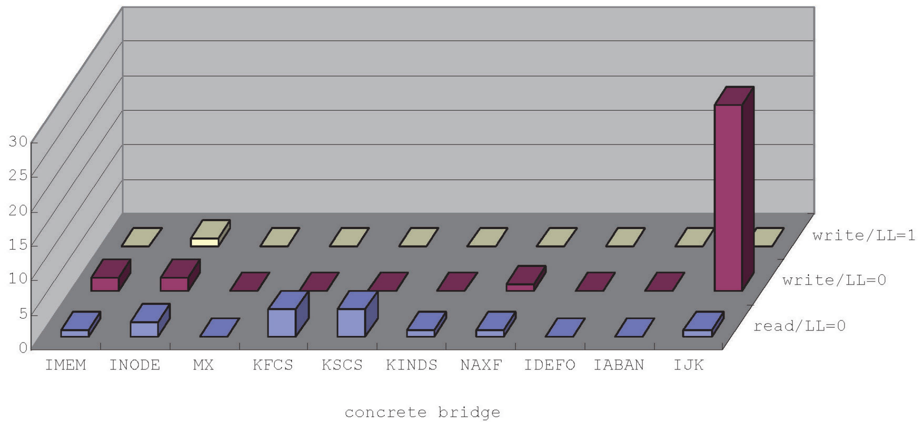


Fig. 6. Results of mediator maker analysis when assuming variables used in the source code of a structural analysis method for steel piers.

The mediator maker analyzes all variables in a given source code, and examines the frequency of their appearance. As an example, the source code of an analysis method of concrete bridge pier is analyzed, and the frequency of appearance is shown in Fig. 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 can be seen, variables INODE, IMEM, and IJK are assumed as node number, element number, and time increment number, respectively, which are correct assumptions.

Examples of the visualization of VC are shown in Fig. 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 a color. As expected, structures of the identical configuration and material properties have different responses because strong ground motions input to them are not the same due to the difference in local ground structures that results in different amplifications of earth-

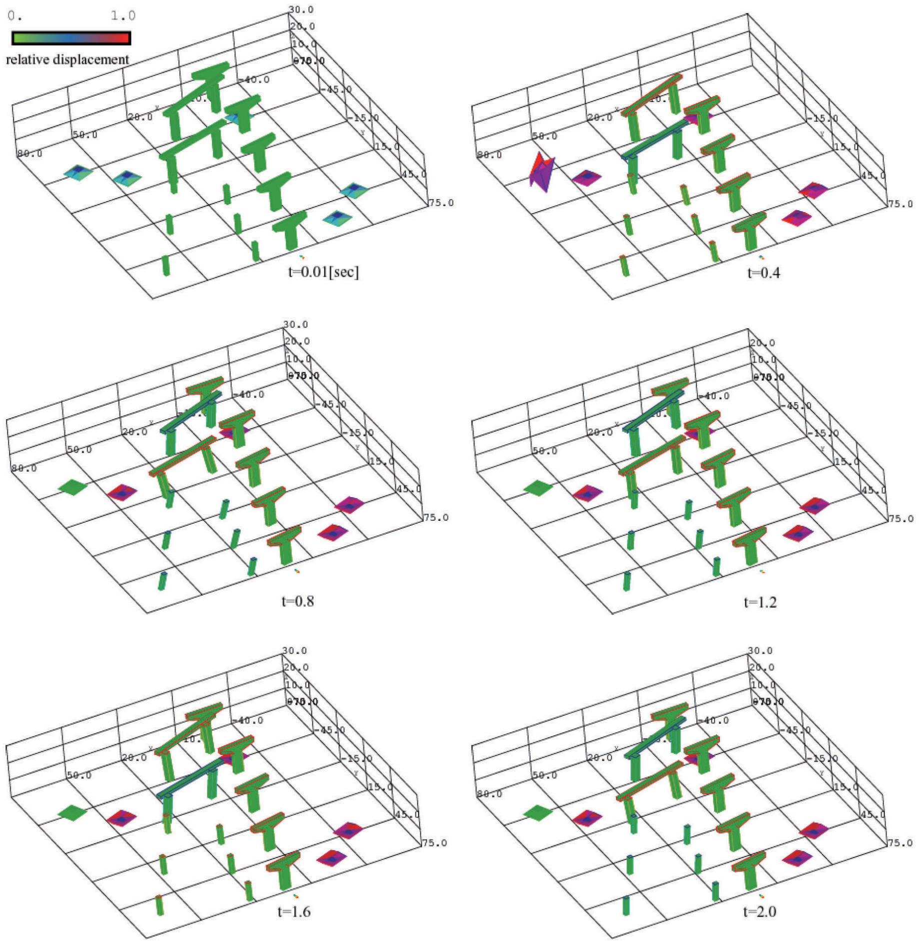
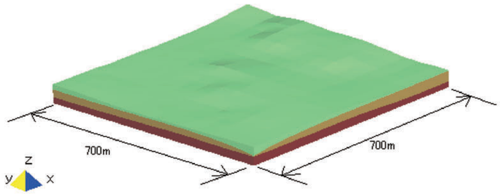


Fig. 7. Dynamic images of VC; snap shots taken every 0.2 seconds.

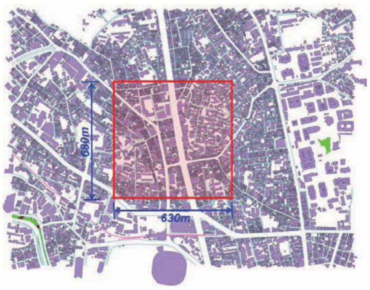
quake ; see ground molds. Structures of different kinds have responses that are mainly governed by natural frequency ; for instance, concrete and steel piers located at the center of VC cause a large contrast in amplitude of displacement, and the maximum displacement of the concrete pier is just 20% of that of the steel pier.

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

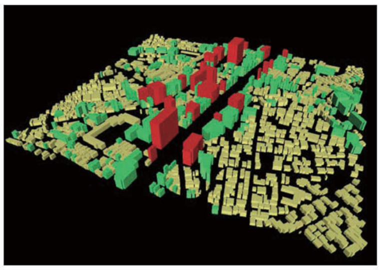
The results discussed above are generated by a prototype IES. A more advanced IES is being constructed so that it can cope with commercially available GIS, which cover most major cities in Japan.



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

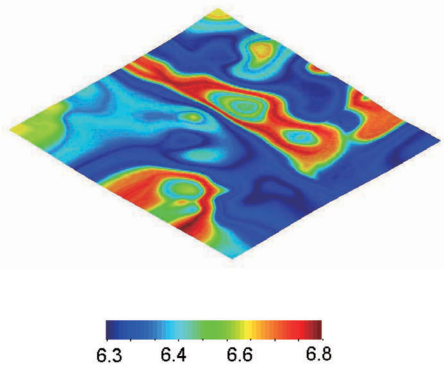


small area of Bunkyo City

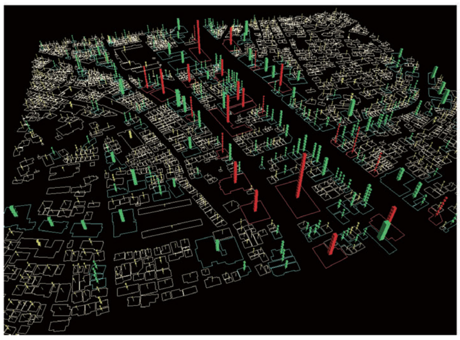


building models; red, green and yellow are for high, middle and low residential houses and buildings

Fig. 8. A small area of Bunkyo City in Tokyo which is made automatically by IES; data stored in a commercially available GIS are used.



distribution of seismic index; waves measured at Takatori JR Station for Hyogoken-Nanbu Earthquake, 1995, are used as input to boundary conditions



response of building models; multi mass system models are used

Fig. 9. Results of the earthwuake and structure response simulations made by IES for the small area of Bunkyo city in Tokyo.

The basic structure and function are the same ; only the interfaces between the kernel and GIS are updated. An example of this IES is shown in Fig. 8 : the model is made for a small area of 500×500 [m] in Bunkyo City, Tokyo. Computer models are made automatically for underground structures and several hundred buildings. The results of the earthquake simulation and the structure response simulation are shown in Fig. 9.

5. Concluding Remarks

IES is being developed to deliver local government officials and residents quantitative information about possible earthquake hazards and disasters that are obtained by means of large-scale simulations of all earthquake phases for a given earthquake scenario. 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 a macro-micro analysis method, and it is necessary to improve the method so that a more accurate prediction with a higher resolution can be achieved. Also, a larger scale simulation is needed for IES to be applied to a larger area.

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