# Application of Macro-Micro Analysis Method to Estimate Strong Motion Distribution and Resulting Structure Response

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## Abstract

**The macro-micro analysis method, which is based on the multi-scale analysis, is to compute strong motion distribution with highest spatial and temporal resolution. The linkage of the multi-scale analysis solutions is modified, and the accuracy of the simulation is improved. The computed strong motion distribution is used to shake a computer model of an actual town, which consists of an underground structure model and building models. The model is constructed by using data which are stored in Geographical Information System, and dynamic responses are computed for all buildings subjected to the strong motion at each site.**

## Introduction

For the safety of a metropolis against a huge earthquake, it is essential to predict possible disaster in a realistic manner such that more effective countermeasures are made. Such prediction requires the high accuracy for strong motion simulation as well as the reliability of a model of the target metropolis. However, there are the following two difficulties: 1) enormous computer resources that are needed by the prediction of high spatial resolution; and 2) the limitation of available data for underground and man-made structures. Therefore, we have been developing a multi-scale numerical analysis method, called the macro-micro analysis method, for computing the earthquake simulation with high resolution (Ichimura and Hori, 2000[1]), and proposing a methodology of constructing simulation models by making use of data which are stored in Geographical Information System (GIS).

In this paper, we report the current state of the macro-micro analysis method and its application to an earthquake simulation of a town. A key issue of the macro-micro analysis method is the multi-scale analysis which first computes waves with a lower spatial resolution and then calculates waves with a higher one. Thus, a rational linkage of waves with the different resolutions, which, in seismology, corresponds to the extrapolation from lower frequency wave components to higher ones, must be made. For the earthquake simulation, we construct a computer model for a town in which around 150 building models are located. The actual GIS data for Roppongi Area, Tokyo, Japan, are used to make the town model, and a wide range of structural responses which vary depending on the input strong motion are obtained.

## Strong Motion Simulator using Macro-Micro Analysis Method

The macro-micro analysis method takes advantage of the multi-scale analysis for efficient and accurate numerical computation and the bounding medium theory for constructing a reliable model for underground geological and ground structures (Ichimura, 2001[2]). These two theories enable it to estimate possible strong motion distribution through numerical computation of the wave propagation processes from a fault to ground surfaces with sufficiently high spatial and temporal resolution even though the data for underground structures are limited.

The multi-scale analysis of the macro-micro analysis method uses spatial coordinates of different length scales. The macro-analysis and the micro-analysis compute the wave propagation in the geological scale with low resolution and in each town or ward with high resolution, respectively. That is,

$$u_i(x,t) = u_i^0(x,t) + \varepsilon u_i^1(x,y,t). \qquad (1)$$

where $u_i$ is displacement and $y=x/\varepsilon$ is the fast spatial coordinates with e being the ratio of the two length scales. These $u_i^0$ and $u_i^1$ are computed in the macro-analysis and the micro-analysis, respectively. The linkage between $u_i^0$ and $u_i^1$ is rigorously formulated for lower frequency wave components (<1[Hz]) whose wave length is sufficiently larger than the macro-analysis length scale. However, for higher frequency wave components, we have to extrapolate $u_i^0$ which does not have such components. The extrapolation is made in the following manner:

i) compute a statistical spectral form using past wave records measured at a target point, and extrapolate higher frequency at ground surfaces.

ii) compute vertical distribution of higher frequency wave components assuming local stratified structures, and horizontally interpolate these components.

By substituting the extrapolated $u_i^0$ into Eq. (1), $u_i^1$ is computed for higher frequency components.

Due to the lack in available data, we construct a stochastic model for geological and ground structures as an alternative of a deterministic model. The bounding medium theory provides two deterministic models for the stochastic model, such that the mean responses of the stochastic model can be bounded by the responses of these deterministic models.

In the micro-analysis, non-elastic properties of soil near ground surfaces are accounted for, since these properties influence strong motion distribution significantly. The simple a hysteresis attenuation (HA) model is used as a constitutive relation model. This model gives rather complicated relation for the damping, which, in frequency domain, can be expressed in the following simple form:

$$b_i(x,\omega) = \imath\eta u_i(x,\omega), \tag{2}$$

where $b_i$ is the apparent body force due to damping and $\eta$ is the attenuation constant of the HA model that can be determined from the soil properties.

We show two examples of the strong motion simulation made by the present macro-micro analysis method. The target is Yokohama City (Fig. 1), and the characteristics of the earthquakes are summarized in Table 1. We compare the simulation results with wave form records which were measured by 12 seismographs operated by Yokohama Strong Motion Observation Network. In Fig. 2, we show the comparison of the velocity wave form at hd01d site; the two models are constructed according to the bounding medium theory, and the results of these models are denoted by optimistic and pessimistic, respectively. As is seen, the agreement is satisfactory. Also, in Fig. 3, the peak ground velocity is compared for the 12 sites. Except for two sites (hd05s and kn03s), the agreement is satisfactory.

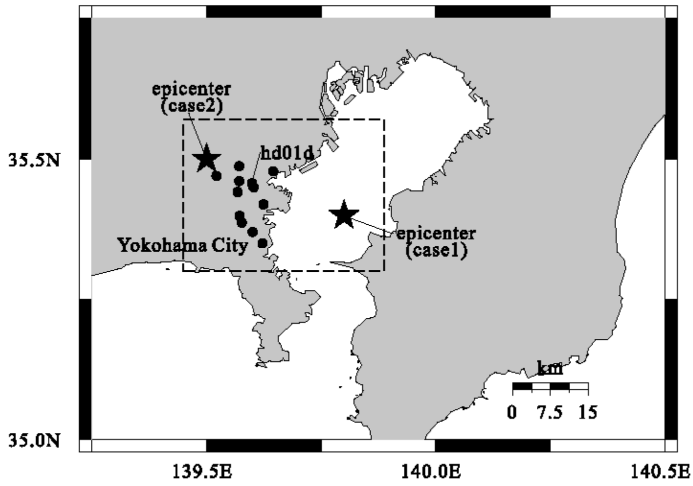



Figure 1: Yokohama city and epicenter of earthquake.

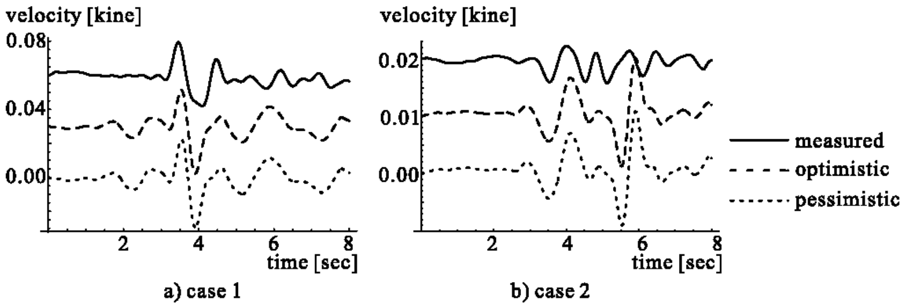


Figure 2: Velocity waveform at hd01d: measured and computed.

Table 1: Properties of earthquake.

| | Date | Lat. | Long. | Depth | Strike | Dip | Rake | Mag. |
|---|---|---|---|---|---|---|---|---|
| case1 | 08/11/1999 | 35.4N | 139.8E | 53km | 62° | 85° | 73° | 4.0Mw |
| case2 | 05/28/1999 | 35.5N | 139.5E | 38km | 283° | 70° | 112° | 3.5Mw |

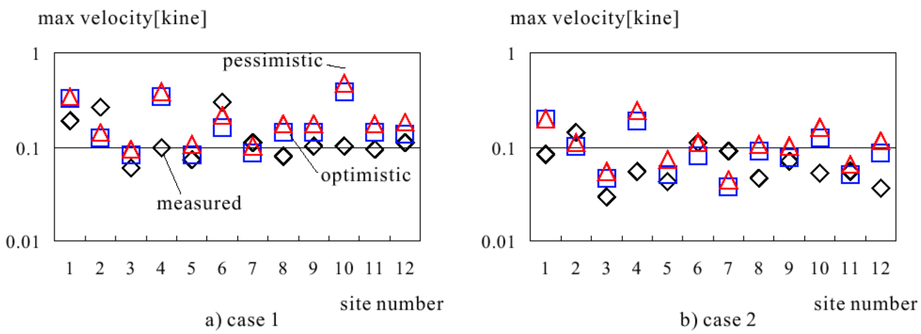



Figure 3: Maximum velocity at each site.

## Modeling Virtual Town and Earthquake Simulation

The accurate strong motion simulation with high spatial resolution can be used to predict possible damages of each buildings and structures, from which earthquake hazards can be understood more realistically. We construct a computer model of an actual town, Roppongi Area, Tokyo, Japan. The target town is for the micro-analysis, and the dimension of the model is 300×300[m] in the EW and NS directions. There are around 150 buildings. The computer model, called a virtual town, consists of the underground structure model and the structure models for all buildings in it. Table 2 summarizes the data required for constructing the virtual town and available in the GIS.

The underground structure model is constructed down to the depth of 60[m]; see Fig. 4. Boring data which are stored in the GIS of this area are used, and six non-parallel surface layers are determined by smoothly connecting the boring data together with modifying the consistency of the layer sequences (Aoyama *et al*. 1997[3]). The elevation of the surface ground is also included in the underground structure model; the elevation data with grid points of 50[m] interval stored in the nation-wide GIS are used.

For each building, we construct a structure model of multi-degree-of-freedom system (MDOFS) (Chopra 2001[4]). This structure model needs the location, the story number, and the dynamic characteristics (say, first few natural frequencies and modes) which determine the manner how the building is shaken (Clough 1993[5]). The location and the structure number are provided by the GIS for buildings located in Tokyo, and the dynamic characteristics are estimated by using the design codes (Paz 1994[6]). A bird view of the virtual town is shown in Fig. 5, where the MDOFS of all the buildings are shown as a cubic column.

The earthquake simulation in the virtual town is carried out by the following manner:

i) carry out the macro-analysis for the geological model, and obtain the input for the micro-analysis by extrapolating the low resolution wave.

ii) carry out the micro-analysis for the underground structure model, and obtain the displacement distribution on the ground surface as time data series.

iii) compute the structure responses by inputting the strong motion to the MDOFS and applying the modal analysis.

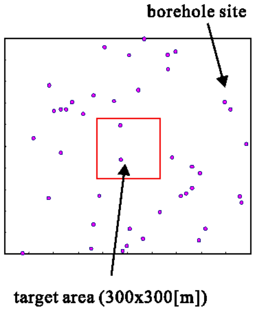
Since the dynamic responses of the MDOFS is discretized as $v = \sum q_n \Phi_n$ where $v$ is the dynamic response, $q_n$ and $\Phi_n$ are the coefficient and the mode, the modal analysis solves the equation of motion for $q_n$ with suitable initial conditions, i.e.,

$$\ddot{q}_n + 2\xi_n \omega_n \dot{q}_n + \omega_n^2 q_n = \ddot{z}_n \quad (3)$$

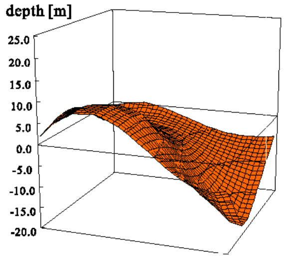
where $\omega_n$ and $\xi_n$ are the natural frequency and damping coefficient, and $z_n$ is the input strong motion that is computed from the ground motion.

Table 2: Data required for analysis models and data currently available in GIS's.

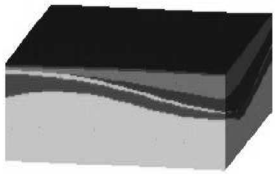
| | required | available |
|---|---|---|
| underground structure | | |
| configuration | boundary depth, soil type, etc. | elevation data(50m[m] mesh GIS data), borehole data |
| material properties | density, wave velocity, non-linear properties | database for soil type-material parameter relation |
| structure | | |
| basic | location, structure type | digitized perspective view |
| configuration | structure dimension, member dimension | height data (satellite image) |
| material properties | member elastic property, member non-elastic property | none |




(a) location of borehole site




(b) example of interface between soil layers:fifth layer and bedrock mass

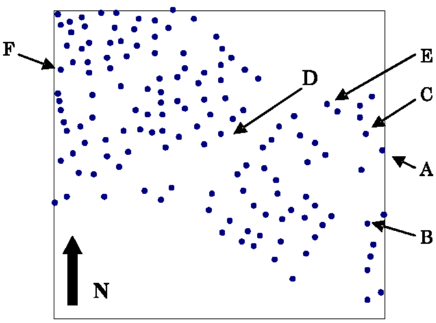


(c) underground structure model

(d) properties of soil layer

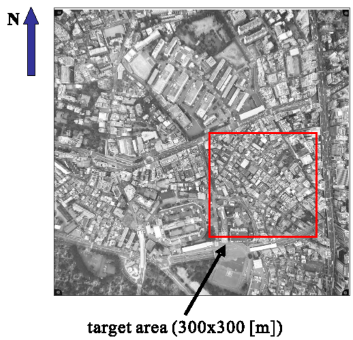
| layer number | soil type | Density *[g/cm 3 ]* | S wave velocity [m/s] | P wave velocity [m/s] |
|---|---|---|---|---|
| 1 | surface soil | 1.625 | 120.0 | 204.0 |
| 2 | loam | 1.550 | 135.0 | 229.5 |
| 3 | sand | 1.800 | 400.0 | 680.0 |
| 4 | clay | 1.750 | 200.0 | 340.0 |
| 5 | fine sand | 1.900 | 425.0 | 722.5 |
| bottom | rock | 1.850 | 600.0 | 1020.0 |

Figure 4: Underground structure model of virtual town: Roppongi Area, Tokyo, Japan.



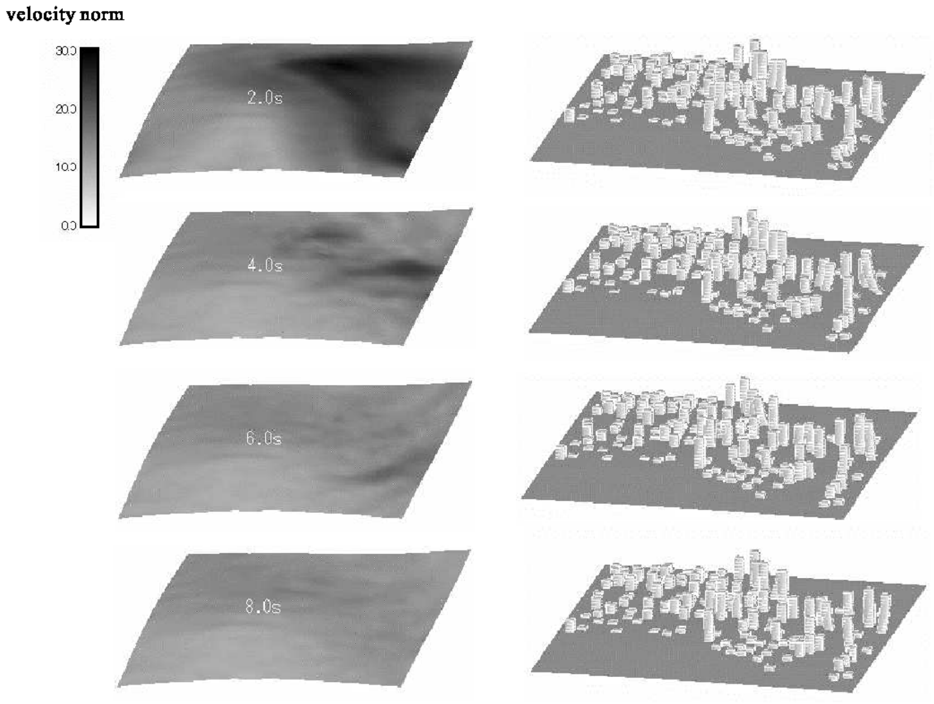

(a) location of building.

(b) bird-view of building.




(c) source satelite photograph for GIS.

Figure 5: Structure models of virtual town.




(a) location of building. b) structural responses.

Figure 6: Example of earhquake simulation using macro-micro analysis method: structure responses are computed by applying modal analysis to mutli-degree-of-freeom system.

Table 3: Results of strong motin distribution: peak ground displacement (PGD) and velocity (PGV) for three different input.

| | | EW | NS | UD |
|---|---|---|---|---|
| PGD [cm] | EW | 3.54 | 0.86 | 0.71 |
| | NS | 0.85 | 4.30 | 0.56 |
| | UD | 0.73 | 0.65 | 2.23 |
| PGV [kine] | EW | 28.75 | 9.42 | 8.27 |
| | NS | 9.78 | 28.08 | 7.15 |
| | UD | 8.43 | 8.25 | 9.57 |

Table 4: Reponses of structure model: maximu displacement [cm].

(a) SRC & RS .

| | type | T1[sec] | EW | NS | UD |
|---|---|---|---|---|---|
| A | SRC | 1.16 | 11.01 | 12.81 | 2.56 |
| B | RC | 0.77 | 4.61 | 4.38 | 1.70 |
| C | RC | 0.77 | 3.38 | 4.20 | 1.44 |

(b) wooden.

| | T1[sec] | EW | NS | UD |
|---|---|---|---|---|
| D | 0.30 | 1.54 | 0.79 | 0.46 |
| E | 0.35 | 1.27 | 0.60 | 0.34 |
| F | 0.55 | 1.71 | 2.67 | 0.79 |

As a simple example, we show snap shots of the earthquake simulation in the virtual town in Fig. 6, when a half period sinusoid wave in the EW direction of the amplitude 1 [cm] and the period 2 [sec] is used as the macro-analysis result. Some concentrations of the strong motion are shown in Fig. 6 a). Even for the simple input earthquake, the complicated ground structures of the virtual town produce spatial variation of the strong motion distribution, and the resulting structure responses also vary for each building as shown in Fig. 6 b).

Tables 3 and 4 summarize the maximum responses of the ground and the structures for three different directions (EW, NS and UD). Six structures with similar dynamic characteristics indicated in Fig. 5 a) are used; A _ C are for relatively tall buildings and D _ F for wooden houses. As is seen, large variability in strong motion is observed in Table 3. This variability is due to the three-dimensional topographical effects of the underground structures, which causes variability in the structure responses. It should be noted that such variability depends on the location of the structure as well as the input earthquake.

## Concluding remarks

A simple earthquake simulation in a virtual town is made by applying the macro-micro analysis method. Such simulation becomes more realistic and reliable as the earthquake (wave) simulation is made with higher accuracy and resolution. Although the limitation of constructing a computer model should not be underestimated, the earthquake simulation will be useful for the earthquake hazard and disaster prediction.

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## References

[1] Ichimura, T. and M. Hori, 2000, *Macro-Micro analysis for prediction of strong motion distribution in metropolis,* J. Struct. Eng./Earthquake Eng., JSCE, **I-52(654),** 51-62.

[2] Ichimura, T, 2001, *Development of strong motion simulator with High spatial resolution based on multi-scale analysis theory,* Doctor Thesis of Department of Civil Engineering, University of Tokyo.

[3] Aoyama, T., Shiono, K. , Masumoto, S. and Noto, T., 1997, *Optimal Determination of Discontinuous Surfaces,* Geoinformatics, **8(3)**, 157-175.

[4] Chopra, A.K. 2001, *Dynamics of Structures, Theory and Applications to Earthquake Engineering,* Prentice Hall.

[5] Clough, R.W. and Penzien, J., 1993, *Dynamics of Structures, Second Edition,* McGraw-Hill, Inc.

[6] Paz, M. (editor), 1994, International handbook of earthquake engineering codes, programs, and examples, New York : Chapman & Hall.