An Integrated Geologic- and Engineering-Length Scale Forward Modeling for Response Estimation of Nuclear Power Plant due to the Rupture of a Nearby Fault

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SUMMARY:
In this paper we discuss the development of seismic response estimation method for nuclear power plant building structures based on fault-structure system. In analysing this system, we model the source process, seismic wave propagation in the crust and soil layers, and the dynamic response of the building structure. Due to the varied length-scales involved in simulating from the fault rupture to the building dynamic response, the computation cost of analysis is high. Thus, we combine a multiscale approach called the Macro-Micro Analysis (MMA), and distributed-memory parallel computing. As an application example, we compute the response of a model of a nuclear power plant building using the 2007 Chuetsu-oki earthquake as the source. We target accuracy of the forward modelling up to 1.0 Hz. Advantages for the analysis of NPP building in the structure-level and in the element level are discussed.

Keywords: fault-structure system, multiscale modelling, large scale computing, 3D Finite Element Method

1. INTRODUCTION

The safety of nuclear power plants (NPP) is a major concern in seismically active regions. The NPP building must be designed to withstand the ground motion based on the rupture scenarios of nearby faults. Because a NPP building is composed of structural members with varying dimensions, estimating the effect of input ground motion on the structure-level and in the element-level is important. The input ground motion to structures is influenced by several processes – the source process, the seismic wave propagation through the crust, the amplification in soft layers, and the soil-structure interaction. Depending on the scenario, these processes will have varying effect on the input ground motion. In this study, we aim to model all these processes in a three-dimensional model called a fault-structure system.

In the literature, many studies aim to combine the analysis of multiple processes. These studies analyze either (1) from the source process to the local site response or (2) from wave propagation to structure dynamic response (see for example, Moczo et al., 1997; Bielak et al., 2003; Park et al., 2009). Recently, full simulation approaches (from source process to structure dynamic response) have been proposed (see Ichimura et al., 2007; Taborda and Bielak, 2011; Ichimura et al., 2011) owing to the availability of new powerful computers. One approach based on multiscale analysis called, the macro-micro analysis method, or MMA (Ichimura et al., 2007), allows for computing the analysis of fault-structure system efficiently. Recent developments related the MMA (see Ichimura et al., 2011) have focused on accurate and efficient generation of macro and micro analysis models. In this study, our aim is to develop a seismic response estimation method for NPP building structures based on analysing the fault-structure system by the MMA method.

This paper is arranged as follows: First we introduce the fault-structure system analysis by the multiscale approach, MMA. Next we discuss the implementation of FEM and the parallelization approach. Then, we demonstrate its utility in an application example. Finally, we discuss the current results and future targets.

2. FAULT STRUCTURE SYSTEM ANALYSIS

2.1. Fault-structure system problem solved by multiscale analysis

As mentioned, the fault-structure system is a model that includes the fault, the crust and soil layers, and the building structure. Analysis of this system models the source process, the wave propagation in the crust and velocity layers, amplification in the soft soil, and building dynamic response. Figure 2.1 shows a fault-structure system model. One advantage of using the fault structure system is that we can compute the building dynamic response as a direct consequence of modelling all the processes. In this section we discuss the pertinent equations related to the application of MMA to the fault-structure system problem as given in Ichimura et al. (2007). We start with the equation of elastodynamics,

$$d_i\left(c_{ijkl}d_l\left(u_k\right)\right)-\rho\ddot{u}_j=0 \quad , \tag{2.1}$$

where c_{ijkl}, ρ, u_k, d_i, and $(\dot{})$ are components of elasticity tensor, mass density, displacement component, partial differentiation, and time derivative, respectively. In MMA, the solution, u, is approximated by applying the singular perturbation expansion technique:

$$u_k \approx u_k^{(0)}+\varepsilon u_k^{(1)}+\ldots \quad , \tag{2.2}$$

where, in the right hand-side of the above equation, the first term is the solution at low resolution, and the second term is the correction. The parameter, $\varepsilon=X_i/x_i$ is a very small parameter (<<1) that relates the slow spatial variable, X to fast-changing variable, x. Application of Eqn 2.2 to Eqn 2.1 results to the following two equations:

$$D_i\left(C_{ijkl}D_lu_k^{(0)}\right)-R\ddot{u}_j^{(0)}=0 \tag{2.3}$$

$$d_i\left(c_{ijkl}\left(d_lu_k^{(1)}+d_lu_k^{(0)}\right)\right)-\rho\left(\ddot{u}_j^{(1)}+\ddot{u}_j^{(0)}\right)=0 \tag{2.4}$$

where D_i is differentiation with respect to X_i, R is the effective density, and C_{ijkl} is the equivalent elasticity tensor in the domain of the slow spatial variable. In MMA, Eqn 2.3 is the equation for macro analysis, and Eqn 2.4 is the equation for micro analysis. Discretizing Eqns 2.3 and 2.4 by finite element method (FEM), and adding damping and external force leads to the following equation,

$$\mathbf{Ku}+\mathbf{C\dot{u}}+\mathbf{M\ddot{u}}=\mathbf{f} \tag{2.5}$$

where **K**, **M**, **u** are stiffness matrix, mass matrix, and displacement component, respectively. **C** is a Rayleigh damping matrix, and **f** is external nodal force vector (the nodal force vector is added only in the macro analysis to represent the input source). Solving Eqn 2.5 for macro analysis in a low resolution model allows for computing the seismic wave propagation problem in a large domain. Since the accurate solution is needed only in the domain near the structure (the correction for low resolution is added by modelling the crust and low velocity layers that have effect on the high resolution component of the solution), the domain of micro analysis model can be made sufficiently small. We can then use a fine mesh of the soil and building structure model in the micro analysis. This computation approach of MMA makes it efficient to handle high fidelity numerical models for both analyses. Figure 2.1 also shows the MMA approach in solving the fault-structure system analysis.

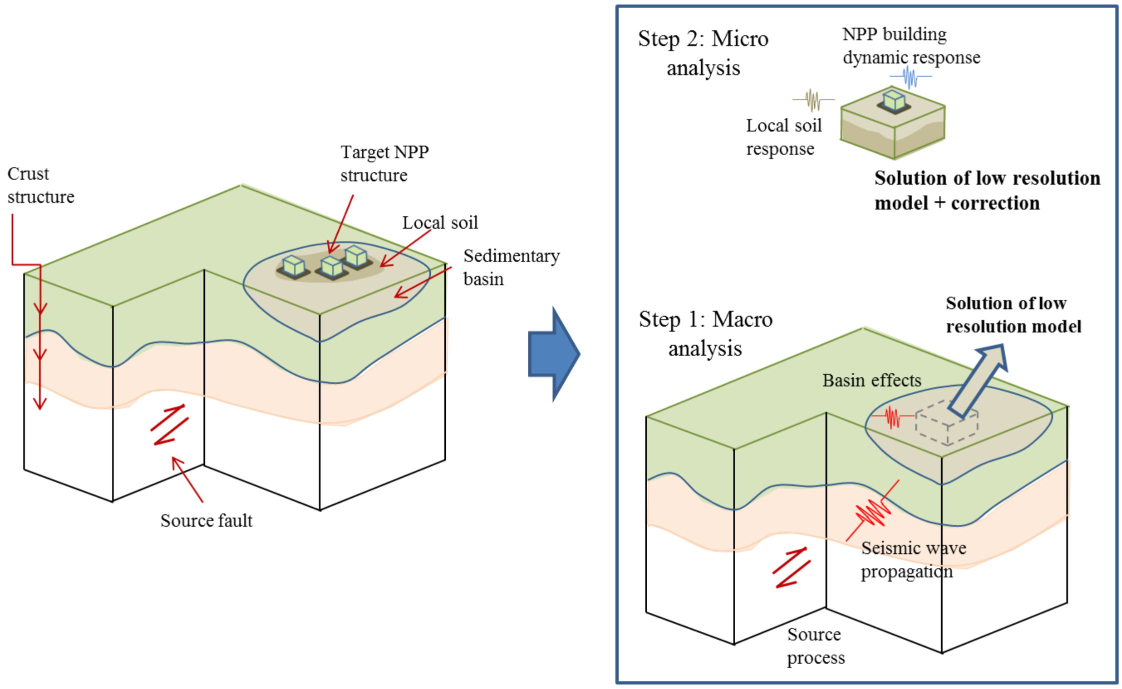


Figure 2.1. Left: the fault-structure system; Right: MMA approach in solving the case of NPP building seismic analysis based on the fault-structure system.

2.2. Parallel model generation and analysis

For time integration, we implement the implicit Newmark-β method (β=0.25; γ=0.5) to Eqn 2.5,

$$\left(\mathbf{K}+\frac{2}{\Delta t}\mathbf{C}+\frac{4}{\Delta t^2}\mathbf{M}\right)\mathbf{u}^{n+1}=\left(\frac{2}{\Delta t}\mathbf{C}+\frac{4}{\Delta t^2}\mathbf{M}\right)\mathbf{u}^{n}+\left(\mathbf{C}+\frac{4}{\Delta t}\mathbf{M}\right)\mathbf{v}^{n}+\mathbf{M}\mathbf{a}^{n}+\mathbf{f}^{n} \tag{2.6}$$

where Δt is the time increment, and n is the n^{th} time step. To solve the above linear equation, we use the preconditioned conjugate gradient method with a preset convergence criterion.

It is noted that when computing the MMA, the computation cost of macro analysis is sensitive to the target frequency, because the domain size of the model is fixed (by the distance of the source and the structure) and increasing the target frequency leads to finer mesh sizes. In the case of micro analysis, the domain size of the model can be reduced as long as the accuracy of solution is sufficient around the structure. Coding the macro analysis then requires an additional effort to reduce the computation time. For this purpose, we apply domain decomposition, and extend the linear solver of the macro analysis to distributed-memory parallel computing.

When the problem setting for macro analysis requires a large domain and fine mesh, we anticipate a high computation cost even in the model generation step (before the analysis step). Thus, it is advantageous to apply parallel computing from this step. A method that subdivides the model before mesh generation is called prepartitioning. The effectiveness of the prepartitioning method depends on how well it works with the mesh generator in order to manage the finite element distribution and node compatibility at the interface between adjacent subdomains (see Galtier and George (1996) for details related to prepartitioning). In this study, since the three-dimensional model is meshed in hybrid-grid (following Ichimura et al, 2009), we can develop the prepartitioning approach to automatically locate the subdomain boundaries and achieve simple domain splitting. In this study, we choose a two-dimensional partitioning as shown in Fig 2.2. We locate the subdomain boundaries where octree boundaries (Bielak et al., 2005; Ichimura et al, 2009) lie in order to smoothly split a domain perpendicular to the surface. In the same principle, we then overlap the horizontal range of subdomains in order to satisfy the node compatibility after independent mesh generation.

After the FE meshes are generated, each subdomain is assigned to one processing element and continues to the analysis step. In order to update the solution at the interfaces, explicit communication between processors is conducted after each matrix vector product and vector reduction in the preconditioned conjugate gradient algorithm.

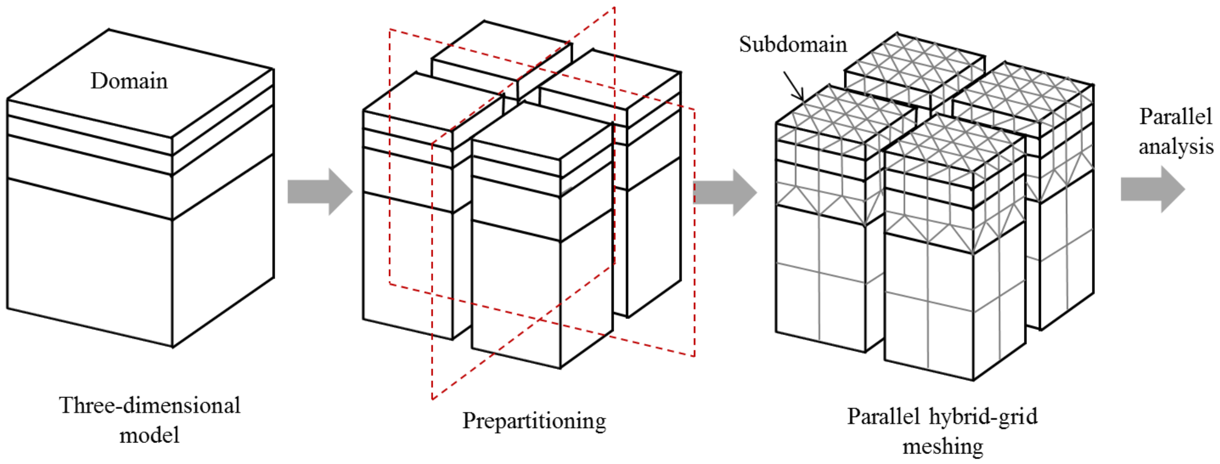


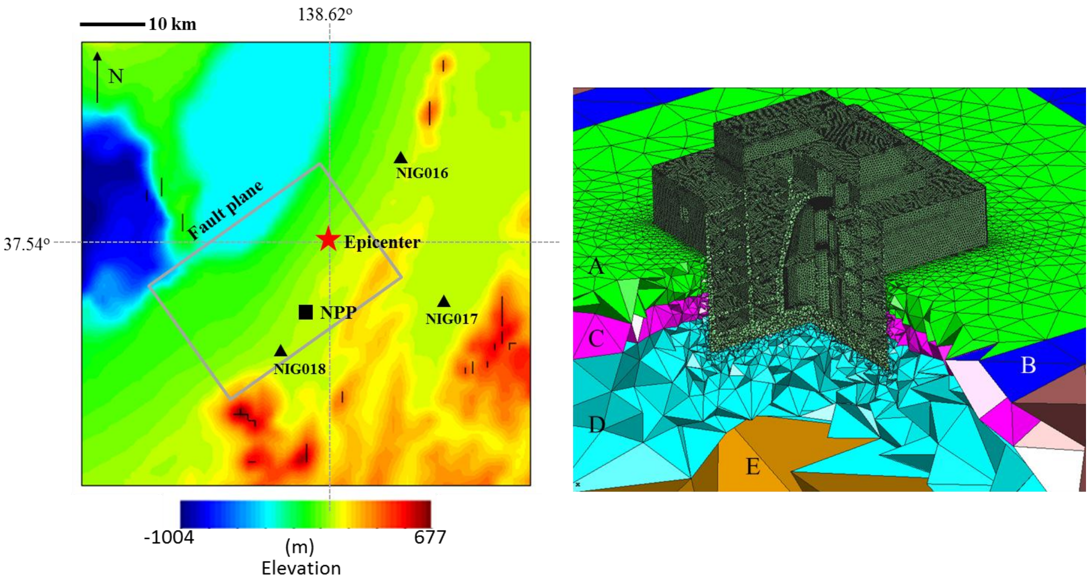
Figure 2.2 Schematics of parallel FE model generation. A three-dimensional model is partitioned perpendicular to the surface before meshing with tetrahedral and voxel finite elements. Each subdomain is assigned to a computer processing element for analysis.

3. APPLICATION EXAMPLE

In this section, we demonstrate the application of the multiscale analysis method employing fault-structure system for the seismic analysis of a model of nuclear power plant (NPP) building structure. Figure 3.1a shows the problem setting for the application example. We set the target frequency to 1.0 Hz (numerical verification conducted up to this target frequency can be found in Ichimura et al., 2011). For the seismic source we use a fault-model of the 2007 Mw 6.6 Chuetsu-oki earthquake (Miyake et al., 2010). The source information based on the southeast dipping fault model (24 km x 32 km) is used (the verified accuracy of this fault model is only up to 0.5 Hz, however, in order to demonstrate the capability of our fault-structure system analysis method to compute up to the current standard limit of deterministic analysis, we set the target frequency to 1.0 Hz). The hypocenter is located at coordinates: (37.54 N, 138.62 E) and 9.0 km depth. The maximum slip is 1.29 m. The strike and dip values are 34^o and 36^o, respectively. The rake values are as given in Miyake et al., 2010.

We generate the macro analysis model based on the JSHIS model for Chuetsu region. Table 3.1 gives the size of the simulation domain. The required FE mesh sizes vary from 360.0 m to 45.0 m. based on the mechanical properties of the crust layers (see Table 3.2), and mesh criterion of 10 elements per shear wavelength. For the micro analysis model (see Table 3.1 for the details of the simulation domain), we use the NPP building structure model of the CREST project of Japan. The mesh size of the soil structure with the NPP building structure is based on the mechanical properties of soil near the NPP and NPP building (see Tables 3.3 and 3.4, and Fig. 3.1b). In total, the number of nodes in the macro and micro analysis models are 140,646,746 and 485,027, respectively. For computing the damping parameters, we refer to Bielak et. al, (2005). For the time integration, we use a time step size of 0.01 seconds (s), and total simulation time of 20.48 s. For linear equation solver, the convergence criterion is set to 10^{-6}.

Figure 3.2 shows the results of macro analysis: the distribution of displacement components is given at different time steps. Figure 3.3 shows the corresponding deformation of the NPP model as computed in micro analysis. Figure 3.4 shows the results of postprocessing: the distribution of maximum shear strain in two orthogonal sections of the NPP building.



(a) (b)

Figure 3.1 (a) Problem setting for application example. The NPP building (black square) is situated above the fault plane (grey rectangle). For reference, the locations of KNET seismic stations (black triangle) are plotted. The distance between the NPP and the epicenter is about 14.3 km. (b) NPP meshed model and soil layers.

Table 3.1. Domain size of macro and micro analysis models

Macro analysis model	Along EW direction:	69.12 km
	Along NS direction:	69.12 km
	Depth:	45.0 km
Micro analysis model	Along EW direction:	0.54 km
	Along NS direction:	0.54 km
	Depth:	0.135 km

Table 3.2. Mechanical properties of crust layers (Macro analysis model)

Macro model	Layer 1 (top)	Layer 2	Layer 3	Layer 4	Layer 5	Layer 6
P-wave (m/s)	1700	2275	3225	3875	5000	5375
S wave (m/s)	450	875	1550	2025	2700	3100
Density (kg/m^3)	1900	2050	2275	2400	2500	2625
Q	60	115	150	200	200	275

Table 3.3. Mechanical properties of soil layers (Micro analysis model)

Micro model	Layer A	Layer B	Layer C	Layer D	Layer E
P-wave (m/s)	400	475	625	600	1950
S wave (m/s)	300	300	300	475	600
Density (kg/m^3)	1825	2000	1775	1700	1950
Q	10	10	10	20	80

Table 3.4. Mechanical properties of NPP building model (Micro analysis model)

NPP model	
Material	Reinforced concrete
Youngs modulus, *E*	2.10 x10^9 (kg/m^2)
Shear modulus, *G*	9.0 x 10^7 (kg/m^2)
Density, ρ	2.4 x 10^3 (kg/m^3)
Poisson's ratio, η	0.17

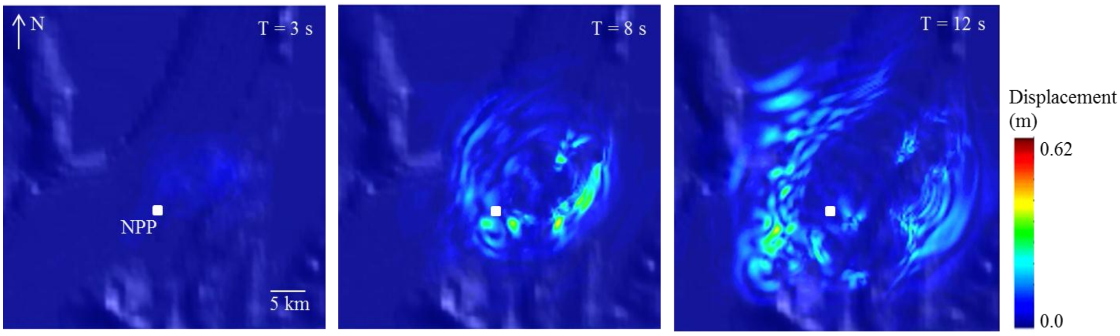


Figure 3.2. Macro analysis results: distribution of displacement norm at the surface at different time steps (N-north direction).

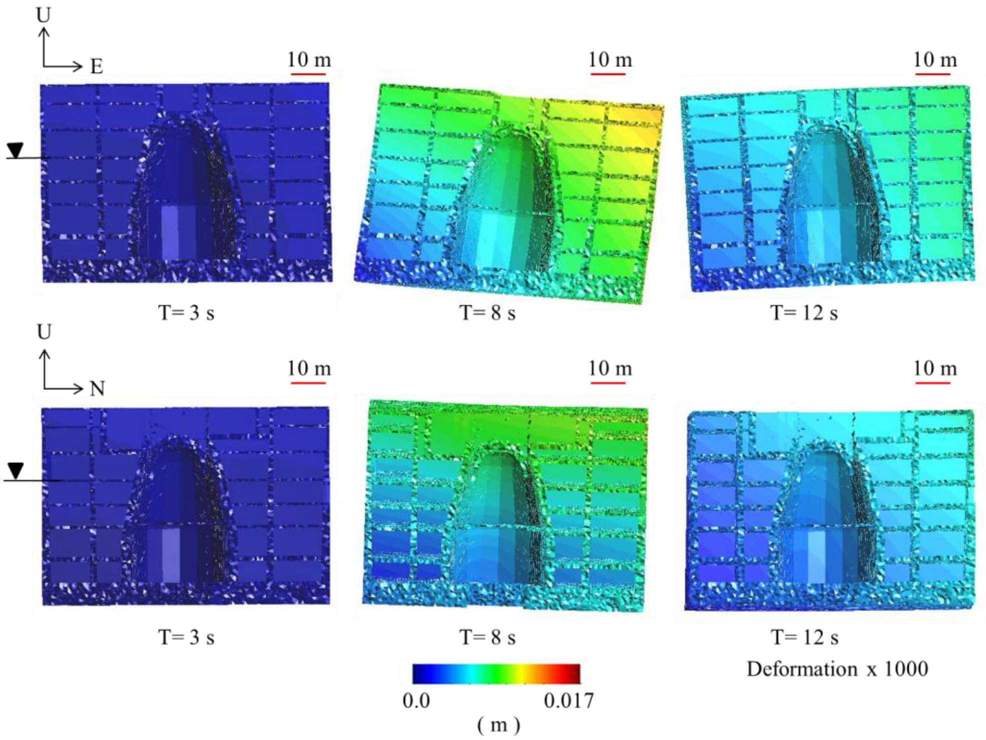


Figure 3.3. Micro analysis results: Top figure shows deformation at midsection along EW direction. Bottom figure shows deformation at midsection along NS direction (U-up direction, E-east direction, N-north direction).

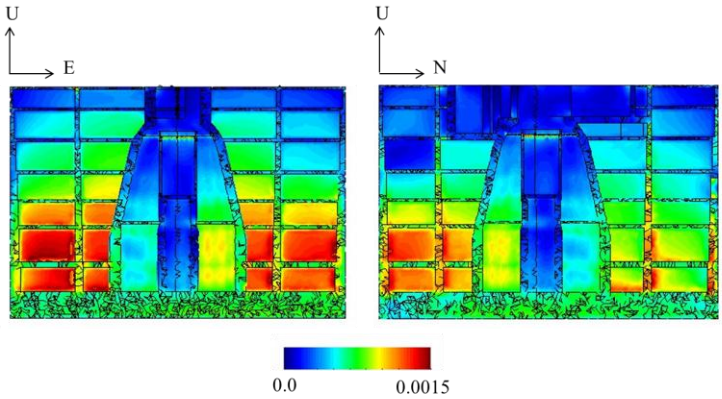


Figure 3.4. Micro analysis results: Distribution of maximum shear strain in the NPP walls by cutting at midsection. U-up direction, E-east direction, N-north direction.

4. DISCUSSIONS AND CONCLUDING REMARKS

In Fig. 3.2 we observed that the wave propagation at the surface was affected by the crust structure and the fault model. There are regions where the amplitude of seismic waves is high, while some regions experienced low amplitude. The computed deformations in Fig. 3.3 show that the building structure responded to the ground motion non-uniformly. As shown in Fig 3.4 (postprocessed results of micro analysis), the maximum shear strain are unevenly distributed in the interior walls of the building. These results suggest that three-dimensional modelling of all the processes is significant for seismic analysis of NPP when considering the rupture of a nearby fault. It is clear that the distribution of ground motion is spatially-varying, and affects the response of the structure in both the structure- and element-level.

In this study we have presented the development of seismic response estimation method for NPP building structures based on fault-structure system. The application of a multiscale approach realized the analysis up to the engineering-length scale. Moreover, the implementation of computing techniques (as given in Ichimura et al., 2009; Ichimura et al., 2011; and the parallel computing approach in this study) realized the large-scale simulation using high-fidelity model. However, such deterministic approach is still mostly suited to long-period simulations due to limitation in accuracy of input parameters. Nevertheless, it presents several advantages for practical application to NPP seismic analysis: (1) estimation of three-dimensional response as affected by source fault and the geologic setting; (2) computing for building structure response in high resolution relevant for estimating stress and strain; and (3) capability to use high fidelity model for analyzing the nonlinear behavior of soil and building structure in the next step.

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REFERENCES

Moczo, P., Bystricky, E., Kristek, J., Carcione, J. M., Bouchon, M. (1997). Hybrid Modeling of P-SV Seismic Motion at Inhomogeneous Viscoelastic Topographic Structures. *Bulletin of Seismological Society of America.* **87:5**, 1305-1323.

Bielak, J., Loukakis, K., Hisada, Y., Yoshimura, C. (2003) Domain Reduction Method for three-dimensional earthquake modeling in localized regions, Part I: Theory. *Bulletin of Seismological Society of America.* **93:2**, 817-824.

Park, D., Sagong, M., Kwak, D-Y, Jeong C-G. (2009). Simulation of tunnel response under spatially varying ground motion. Soil Dynamics and Earthquake Engineering. **29**, 1417-1424.

Ichimura, T., Hori, M. & Kuwamoto, H. (2007). Earthquake motion simulation with multiscale finite element analysis on hybrid grid. *Bulletin of Seismological Society of America.* **97:4**, 1133-1143.

Taborda, R. and Bielak, J. (2011) Large-scale earthquake simulation: Computational seismology and complex engineering systems. *Computing in Science and Engineering*. 14-26.

Ichimura, T., Hori, M., Quinay, P. E., Wijerathne, M. L. L., Suzuki, T. & Noguchi, S. (2011). Comprehensive numerical analysis of fault-structure systems – Computation of the large-scale seismic structural response to a given earthquake scenario -. *Earthquake Engineering and Structural Dynamics.* DOI:10.1002/eqe.1158.

Galtier, J. and George, P. L. (1996). Prepartitioning as a way to mesh subdomains in parallel. *5th International Meshing Roundtable*, Sandia National Laboratories, 107-121.

Ichimura, T., Hori, M. & Bielak, J. (2009). A hybrid multiresolution meshing technique for finite element three-dimensional earthquake ground motion modeling in basins including topography. *Geophysical Journal International.***177**, 1221-1232.

Bielak, J., Ghattas, O., Kim, E.-J. (2005). Parallel octree-based finite element method for large-scale earthquake ground motion simulation. *Computer Modeling in Engineering and Sciences*.**10:2**, 99-112.

Miyake, H., Koketsu, K., Hikima, K., Shinohara, M., Kanazawa, T. (2010). Source Fault of the 2007 Chuetsu-oki, Japan Earthquake, *Bulletin of Seismological Society of America*, **100:1**, 384-391.

Japan Seismic Hazard Information Station, Japan National Research Institute for Earth Science and Disaster Prevention, http://wwwold.j-shis.bosai.go.jp/j-shis/ .
K-net Kyoshin Network, Broadband Seismograph Network, Japan National Research Institute for Earth Science and Disaster Prevention, http://www.k-net.bosai.go.jp .