Computational Disaster Mitigation and Reduction Research Unit

1. Team members

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2. Research Activities

Computational disaster mitigation and reduction research unit is aimed at developing advanced large-scale numerical simulation of natural disasters such as an earthquake, tsunami and heavy rain, for Kobe City and other urban areas in Hyogo Prefecture. Besides for the construction of a sophisticated urban area model and the development of new numerical codes, the unit seeks to be a bridge between Science and Local Government for the disaster mitigation and reduction.

Our research unit addressed the following research objects in this fiscal year:

1) A next generation urban area model will use a few Geographical Information Systems (GIS). A serious bottle neck of using different GIS's is that each system has its own coordinate system. For data stored in different GIS's, therefore, we have to connect data using a common coordinate system. A methodology of establishing connection based on "Land Address" is developed. The methodology extracts a polygon which is separated by Ward Boundary, and then associates the polygon to the common coordinated system, using string data and the local coordinate. Based on this methodology, we develop a prototype of a module which automatically connects data in different GIS's.

2) Liquefaction is a ground failure which is induced by sudden rise of underwater ground pressure when strong ground motion hits loosened sand. Since the governing equations are found for this coupling problem, we study the stability of the solution and show that it is anisotropy and particle detaching that loses the stability when a *seed* of liquefaction starts to grow; we make linear perturbation analysis for the governing equation, simplifying non-linear properties of soil deformation. Using a finite element program, we numerically confirm that while anisotropy produces temporal increase in water pressure, particle detaching spreads water pressure increase spatially.

3) It is inevitable to use high performance computing in solving earthquake disaster problems for a larger urban area subjected to ground motion with long duration. In particular, ground motion amplification processes which take place in surface ground layers with complicated configuration needs analysis of a high fidelity model of the layers which needs large scale computation. Together with HPCI Strategic Program for Innovation Research Field 3, we have developed a non-linear finite

element program for ground motion amplification analysis. It is shown that the developed program is capable to analyze a model of a few ten billion degree-of-freedoms, which is the largest in this class of problems, using the full system of K computer.

3. Research Results and Achievements

3.1. Development of next-generation urban model for Kobe city

In constructing a next generation urban area model, we will have to use a few Geographical Information Systems (GIS). There is a serious bottle neck of using different GIS's, since each system has its own coordinate system; each object in a target area has different *local* coordinate of a GIS, according to which the object is located in it. Therefore, it is necessary to connect data for one object which are stored in different GIS's.

We are developing a methodology of establishing connection based on Land Address (an address managed by the national government to specify the land use). The methodology takes the following procedures: 1) it extracts a polygon for Land Address which is separated by Ward Boundary (a line which separates zone of one Land Address); 2) it seeks local coordinate and string data which are related to the polygon; and 3) it assigns the polygon to a common coordinate, using the local coordinate and the string data. It should be noted that unlike easiness of manual processing of seeking a common coordinate, automated and robust processing is difficult since there are many cases for the spatial relation between the polygon and the local coordinate.

Based on this methodology, we have developed a prototype of a module which automatically connects data of one object stored in different GIS's. The current target is an object for a residential house or building; see Fig. 3.1.1. We extract data for such a structure which are stored in a commercial GIS and a GIS managed by a local government, in order to construct an analysis model for seismic response analysis. Robustness is essential for this data extraction. In visualizing the seismic response, we have to convert the results of the seismic response analysis in the form that commercial software of visualization is able to process. Flexibility is essential for this data conversion since there a few choices of the commercial software. The prototype is developed to eliminate or minimize manual processing of the data extraction and conversion.

As the number of GIS's increases and more objects are processed, the efficiency of data extraction and conversion needs to be improved. In Fig. 3.1.2, we show a schematic view of the improving the efficiency in which the architecture of the program is changed. It is natural to use data processing such as extraction and conversion as subsidiary functionality in applying the numerical computation. However, the architecture based on this standard treatment cannot make high efficiency, as it needs frequent communication with the numerical analysis method. Hence, we change the architecture so that direct read/write for the data processing is realized. This treatment makes the data processing a major functionality rather than a subsidiary functionality. While coding is tough to exclude manual

Fig. 3.1.1 Extracted data for Land Address. Red lines stand for Ward Boundary and polygons surrounded by red lines are an area of Land Address.

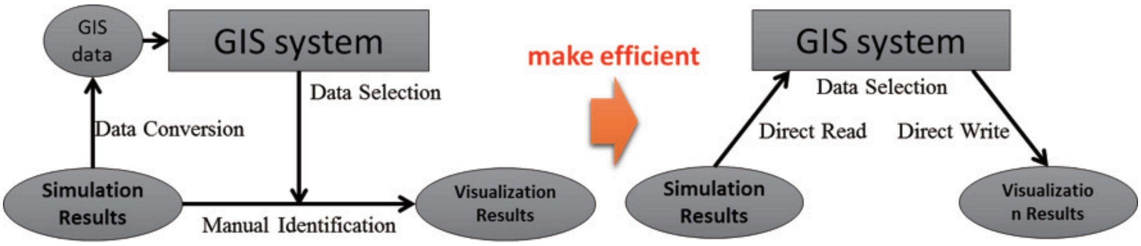


Fig. 3.1.2 Improvement of the efficiency in the GIS data processing with interactive selections.

processing, the present prototype succeeds to make efficient data processing.

3.2 Numerical simulations for stability analysis of liquefaction

In the fiscal year of 2013, we showed that dilatancy played a key role in the stability of the solution of the governing equation of a dynamic problem of soil-water coupling. We obtained a theoretical threshold value for the dilatancy at which liquefaction was initiated.

3.2.1 Mathematical model

We start from the governing equations of a dynamic problem of soil-water coupling. Denoting by $\boldsymbol{u}$ and p the perturbations of the increment of soil displacement and water pressure, we write the governing equation as

$$\begin{gathered}\rho \mathrm{D}^2 \boldsymbol{u} - \boldsymbol{\nabla} \cdot (\boldsymbol{c} \colon \boldsymbol{\nabla} \boldsymbol{u}) + \boldsymbol{\nabla} p = \boldsymbol{0}, \\ \boldsymbol{\nabla} \cdot \mathrm{D} \boldsymbol{u} - \boldsymbol{\nabla} \cdot (k \boldsymbol{\nabla} p) = 0,\end{gathered} \tag{3.2.1}$$

where ρ, $\boldsymbol{c}$, and k are density, elasto-plasticity and permeability; $\boldsymbol{\nabla}$ and D stand for spatial and temporal differentiation; and $\cdot$ and : denote the first- and second-order contraction.

As for dilatancy of soil, we introduce anisotropy of elasticity. Here, isotropy means that $c_{ijkl} = \lambda\delta_{ij}\delta_{kl} + \mu(\delta_{ik}\delta_{jl} + \delta_{il}\delta_{jk})$, with (λ, μ) and δ_{ij} being Lame's constants and Kronecker's delta, and anisotropy means non-zero components which relate shear deformation to normal stress, say, $c_{1112} = c_{1113} = c_{1211} = c_{1311} = \alpha$.

Applying the Fourier transform of Eq. (3.2.1) with the kernel of $\exp\left(i(\boldsymbol{\xi} \cdot \mathbf{x} - \omega t)\right)$, we derive the follow characteristic equation for frequency ω and wave number $\boldsymbol{\xi} = \xi(1,0,0)$:

$$r^4 + i r_k r^3 - (1 + r_s^2) r^2 - i r_k r_s^2 r + r_s^2 - 2 r_a^4 = 0, \tag{3.2.2}$$

where r is the non-dimensional frequency, i.e., $r = \omega/\omega_p$ and $r_{s,a,k} = \omega_{s,a,k}/\omega_p$ with

$$\omega_p = \xi\sqrt{\frac{\lambda+2\mu}{\rho}},\quad \omega_s = \xi\sqrt{\frac{\mu}{\rho}}\ ,\quad \omega_\mathrm{a} = \xi\sqrt{\frac{\alpha}{\rho}}\ \text{and}\ \ \omega_k = \frac{1}{\rho k}.$$

If the imaginary part of r is positive, it means an unstable solution since it grows exponentially with respect to time. The critical value of the dilatancy ratio is given as

$$r_a = \sqrt[4]{\frac{\mu}{2(\lambda+2\mu)}}, \tag{3.2.3}$$

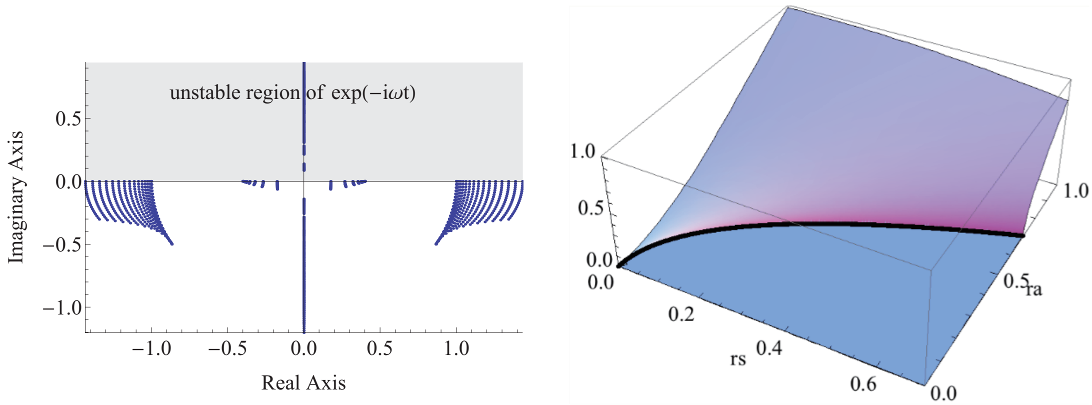
which can be seen in Fig. 3.2.1(b) as an example.

3.2.2 Numerical simulation for spherical perturbations

In the fiscal year of 2014, we have developed and verified a two-dimensional finite element code, which is able to analyze the stability of the governing equation. We use this code for the stability analysis for perturbations in the full three-dimensional settings. The problem setting chosen is for the spherical growth of a perturbation.

Here we only show the unstable solution for a relative large dilatancy ratio. Material prosperities used for simulation are summarized in Table 3.2.1. The results for stable solutions please refer to the related publication. The governing equations are solved numerically in a finite cubic domain (with edge length $L = 0.01$ m) for a spherically symmetrical initial perturbation. The time for a wave with velocity $c_p = 231.46$ m/s propagates from the center to the boundary of the domain is taken as the reference time, denoted by T. As shown in Fig. 3.2.2, the unstable solution is developed when the initial perturbation starts to propagate from the center to the boundary of the domain.

A consequence of the unstable solutions is the concentration of stress, as shown in Fig. 3.2.3. The first stress invariant, $I_1(=\sigma_{kk})$, and the second invariant of the deviatoric stress, $J_2(=\sigma_{ij}\sigma_{ij}/2 - (\sigma_{kk})^2/6)$, are plotted. As is seen, due to the unstable solution, the stress invariants around the center region are accumulated. Further investigations are needed to clarify the possibility of the propagation of the unstable solution considering the formation of "micro cracks", weakening of soil strength when the accumulated stresses exceed a certain yield criterion.



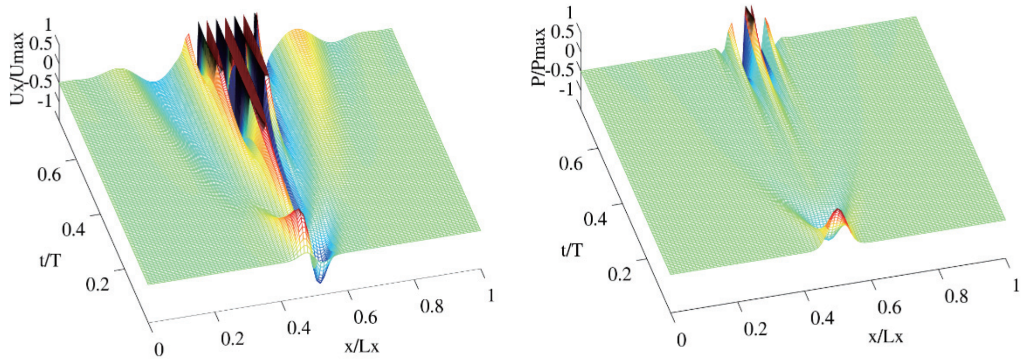
(a) (b

Fig. 3.2.1 Results of theoretical analysis: (a) r on the complex plane for a fixed $r_s = 0.4$ and varying r_k and r_a between 0 and 1. (b) Imaginary part of r and critical dilatancy ratio r_a (indicated as the thick black line) for $r_k = 0.1$, with negative values of the imaginary part truncated as zero.

Table 3.2.1. Material properties for code verification

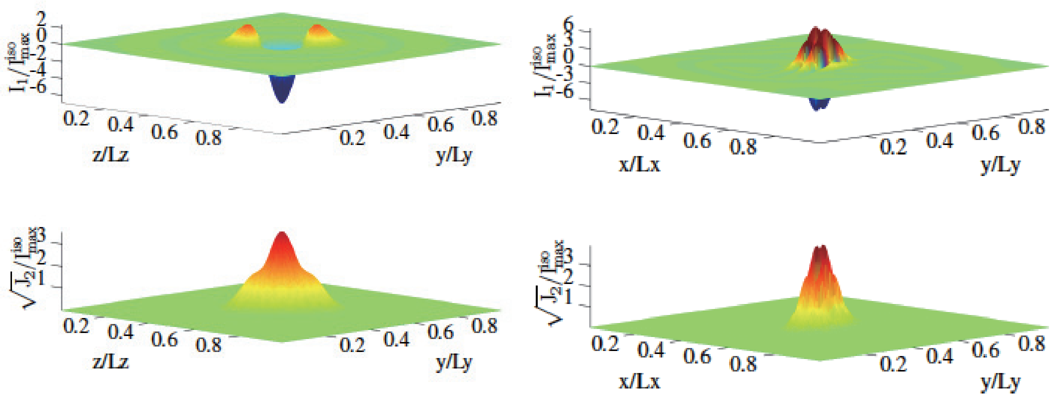
Young's modulus E (MPa)	Poisson's ratio v	Density ρ (kg/m^3)	Permeability k (m^{3}s/kg)	Dilatancy ratio r_a
50	0.4	2000	1.02e-8	$\sqrt{0.30}$

3.3 Numerical simulations for ground motion and seismic response of urban area



(a) (b)

Fig. 3.2.2 Displacement and pressure distribution at the center line ($y = z = L/2$) of the domain: (a) displacement u_x and (b) pressure p. U_{max} and P_{max} are computed from the same simulation settings without considering dilatancy.



(a) (b)

Fig. 3.2.3 Stress invariant at the center planes at $t/T = 0.74$: (a) $x = L/2$ and (b) $y = L/2$. The reference value I_{max} is computed from the same simulation settings without considering dilatancy.

Earthquake hazard and disaster which take place in an urban area are physical processes the mechanisms of which are fully clarified. Due to wide area and long time of the entire processes, it requires large scale numerical computation. Moreover, a model of high fidelity is needed in order to fully capture detailed geometrical configuration of the area and heterogeneous material properties. A three-dimensional finite element method is a unique choice of the numerical analysis, even though simpler analysis methods such as finite difference method have been used with approximation of topographical effects on the physical processes.

High performance computing that is realized by K computer is a computer resource that is able to carry out the large scale numerical computation of the three-dimensional finite element analysis, even though the analysis uses unstructured grid in order to model non-smooth configuration of the target. In this fiscal year, together with HPCI Strategic Program for Innovation Research Field 3, we have developed a fast solver which is fast and scalable for a sparse matrix.

3.3.1 Formulation of finite element method

The wave equation of solid continuum is the common governing equation for the physical processes of the earthquake hazard and disaster. This equation is converted to the following discretized equation for the finite element method:

$$\left(\frac{4}{\mathrm{d}t^2}\boldsymbol{M}+\frac{2}{\mathrm{d}t}\boldsymbol{C}^n+\boldsymbol{K}^n\right)\delta\boldsymbol{u}^n=\boldsymbol{F}^n-\boldsymbol{Q}^{n-1}+\boldsymbol{C}^n\boldsymbol{v}^{n-1}+\boldsymbol{M}\left(\boldsymbol{a}^{n-1}+\frac{4}{\mathrm{d}t}\boldsymbol{v}^{n-1}\right). \quad (3.3.1)$$

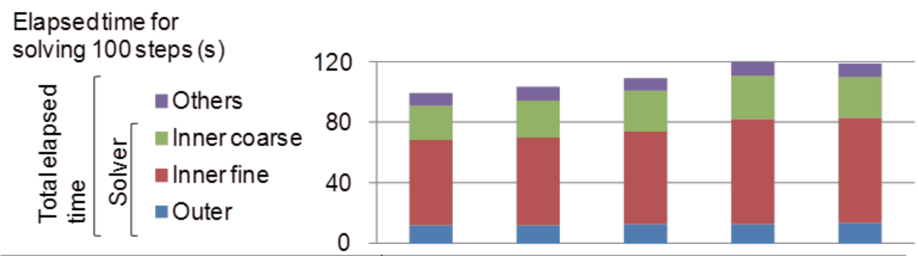
where $\boldsymbol{M}$, $\boldsymbol{C}$ and $\boldsymbol{K}$ are mass, damping and stiffness matrices, respectively, $\delta\boldsymbol{u}$, $\boldsymbol{u}$, $\boldsymbol{v}$, $\boldsymbol{a}$, $\boldsymbol{F}$ and $\boldsymbol{Q}$ are incremental displacement, displacement, velocity, acceleration, external force and unbalanced force vectors, respectively, $\mathrm{d}t$ is time increment, and superscript n stands for the value at the time step (a matrix with superscript n changes due to the material non-linearity). The material non-linearity of soil uses the Ramberg-Osgood model and the Masing rule.

Most of computation time in the finite element method is to compute $\delta\boldsymbol{u}^n$ by solving Eq. (3.1.1). Therefore, it is essential to develop a solver for this equation. A modern supercomputer consists of numerous computation nodes which do not share memory, and it is important to reduce numerical manipulation as well as to minimize inter-node communication in order to achieve large scale and fast numerical computation. Conjugate gradient method (CG) is suitable for parallel computation since it does not require all node computation and all node communication. Hence, there are many improved solvers which are based on CG method.

In applying such a solver, suitable pre-conditioning is needed to improve the nature of the target matrix equation. As is seen in Eq. (3.3.1), the matrix for $\delta\boldsymbol{u}^n$ has a term of $(4/\mathrm{d}t^2)\boldsymbol{M}$, which becomes dominant in the matrix for smaller $\mathrm{d}t$. The convergence of CG method thus is faster, compared with the static problem which ignores the inertia effect. The matrix components change at each time step, and pre-conditioning of decomposing the matrix for $\delta\boldsymbol{u}^n$ becomes computationally expensive. Pre-conditioning which does not require large computation is standard in solving Eq. (3.3.1). We adopt multi-grid and mixed precision for reducing computation and communication for fast finite element solver.

3.3.2 Numerical experiment of earthquake hazard and disaster simulation

The performance of the developed finite element method is shown in Fig. 3.3.1. The scalability of the solver (or the developed finite element method) is good up to the full K computer system. Using this scalable solver we make a numerical simulation of part of Tokyo Metropolis; the size of the area is 3.5 x 3.5 km. The target frequency is 15 Hz, which implies the smallest element size of 0.66 m for the wave velocity of 100 m/s. A model of high fidelity is constructed with the total 40.1 x 10^9 degree-of-freedoms. 1995 Hyogo Earthquake (JMA Kobe) is used as input ground motion, the duration of which is 15 s, and the time increment and the total time step are $dt = 0.001$ s and 15,000, respectively. The full system of K computer is used for this simulation. The natural hazard and disaster simulation is visualized as ground motion distribution and structural seismic response distribution in Fig. 3.3.2. Such visualization will play a role of next-generation hazard map for earthquake.



# of CPU cores (# of compute nodes)	36,864 (4,608)	73,728 (9,216)	147,456 (18,432)	294,912 (36,864)	663,552 (82,944)
Degrees-of-freedom (billion)	1.5	3.0	6.0	12.0	27.0
Degrees-of-freedom per CPU core	41k	41k	41k	41k	41k
Performance of solver (% to peak)	14.49	14.06	13.28	11.82	12.34

Fig. 3.3.1 Size-up scalability of developed finite element method (GAMERA). Elapsed time is for solving 100 time steps of non-linear computation

4. Schedule and Future Plan

In the fiscal year of 2015, we plan to make a next-generation hazard map for Kobe City, using the module of GIS data processing which will be developed by improving the prototype conversion and the numerical analysis methods which are developed together with HPCI Strategic Program for Innovation Research Field 3. We plan to include the following two ingredients: 1) lifeline for water and sewage, which consists of buried pipelines; and 3) ground failure which are induced by liquefaction. For these ingredients, numerical analysis methods developed by expert researchers will be plugged in the integrated system. The key issues are summarized as follows:

1) Construction of next generation urban area model which include lifeline network and underground.
2) Execution of earthquake hazard and disaster simulation based on numerous earthquake scenario
3) Smart visualization of numerical simulation results; if each simulation will produce 10 GB data, we have to deal with 10 TB data for 1,000 earthquake scenarios.

5. Publication, Presentation and Deliverables

(1) Journal Papers

1. Hideyuki O-TANI, Jian CHEN and Muneo HORI: a Template-Based Floor Shape Recognition Applied to 3D Building Shapes of GIS Data, Journal of Japan Society of Civil Engineers, Ser. A1, Vol.70, No.4, I_1124-I_1131, 2014.
2. Hideyuki O-TANI, Jian CHEN and Muneo HORI: Automatic Combination of the 3D Shapes and the Attributes of Buildings in Different GIS Data, Journal of Japan Society of Civil Engineers, Ser. A1, Vol.70, No.2, I_631-I_639, 2014.

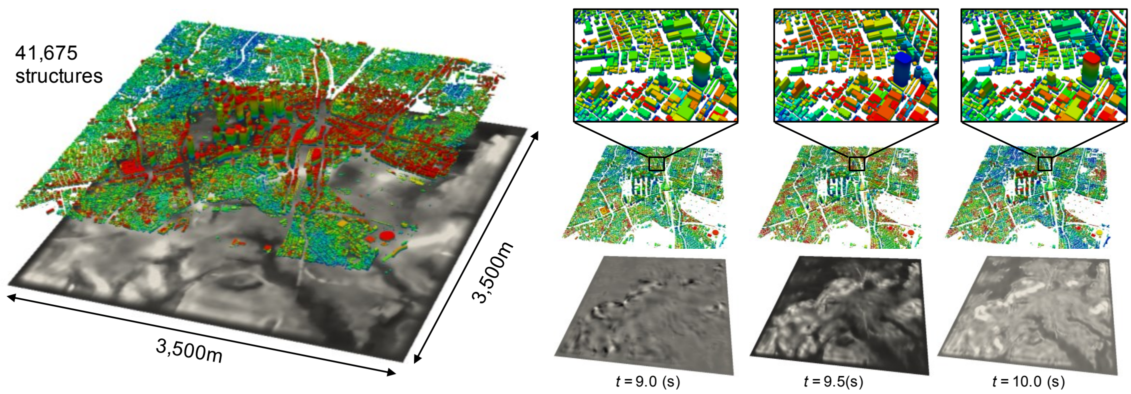


Fig. 3.3.2 Earthquake hazard and disaster simulation for an urban area. Three snapshots are for the distribution of the ground motion and the structural seismic responses at designated time step.

3. Jian Chen, Hideyuki O-tani and Muneo Hori, On mathematical stability analysis of liquefaction considering soil-water coupling, Journal of Japan Society of Civil Engineers, Ser. A2 (Applied Mechanics (AM)), vol.70, No.2, I_641-I_648, 2014.
4. Hans-Georg Matuttis and Jian Chen, Understanding the Discrete Element Method: Simulation of Non-Spherical Particles for Granular and Multi-body Systems, Wiley, 2014.
5. Tsuyoshi Ichimura, Kohei Fujita, Seizo Tanaka, Muneo Hori, Maddegedara Lalith, Yoshihisa Shizawa and Hiroshi Kobayashi: Physics-based urban earthquake simulation enhanced by 10.7 BlnDOF x 30 K time-step unstructured FE non-linear seismic wave simulation, Proceedings of the International Conference for High Performance Computing, Networking, Storage and Analysis (SC '14), Pages 15-26, Gordon Bell Finalist, 2014. 10.1109/SC.2014.7.
6. Tsuyoshi Ichimura, Kohei Fujita, Muneo Hori: Nonlinear Seismic Ground Response Analysis of Local Site Effects with Three-Dimensional High-Fidelity Model, Encyclopedia of Earthquake Engineering, pages 1-8, 2014. 10.1007/978-3-642-36197-5_60-1.
7. Kohei Fujita, Tsuyoshi Ichimura, Muneo Hori, Lalith Wijerathne and Seizo Tanaka: A quick earthquake disaster estimation system with fast urban earthquake simulation and interactive visualization, Procedia Computer Science (The International Conference on Computational Science 2014), Vol. 29, pp. 866-876, 2014. doi:10.1016/j.procs.2014.05.078.
8. Shunsuke Homma, Kohei Fujita, Tsuyoshi Ichimura, Muneo Hori, Seckin Citak and Takane Hori: A physics-based Monte Carlo earthquake disaster simulation accounting for uncertainty in building structure parameters, Procedia Computer Science (The International Conference on Computational Science 2014) , Vol. 29, pp. 855-865, 2014. doi:10.1016/j.procs.2014.05.077.

(2) Conference Papers

1. Jian Chen, Hideyuki O-tani and Muneo Hori, Stability Analysis for Local Liquefaction Initiation of Plane Wave Type, Computer Methods and Recent Advances in Geomechanics, Oka, Murakami, Uzuoka & Kimoto (Eds.), p. 661-666, Taylor & Francis Group, 2015 (14th IACMAG)
2. Kohei Fujita, Tsuyoshi Ichimura, Muneo Hori, Lalith Maddegedara and Seizo Tanaka: Scalable multicase urban earthquake simulation method for stochastic earthquake disaster estimation, Procedia Computer Science (The International Conference on Computational Science 2015), Accepted, 2015.
3. Kohei Fujita, Tsuyoshi Ichimura, Seizo Tanaka, Muneo Hori, Maddegedara Lalith: Numerical Convergence Analysis of Three-dimensional Nonlinear Earthquake Wave Amplification Simulation, Proceedings of The First International Conference of IASUR:

Sustainable Society as Our Challenge, Pages 327-334, 24-27 October 2014.

4. Abdurrahman Sahin, Kohei Fujita, Muneo Hori, Mehmet Ozan Yilmaz: Application of Integrated Earthquake Simulation for the Zeytinburnu District of Istanbul, Computational Engineering and Science for Safety and Environmental Problems (COMPSAFE 2014), 13-16 April 2014.
5. Kohei Fujita, Tsuyoshi Ichimura, Muneo Hori, Lalith Wijerathne, Seizo Tanaka: Urban Earthquake Simulation with Large-Scale 3D Ground Motion Analysis and Structural Response Analysis, Computational Engineering and Science for Safety and Environmental Problems (COMPSAFE 2014, keynote), 13-16 April 2014.
6. Shunsuke Homma, Kohei Fujita, Tsuyoshi Ichimura, Muneo Hori, Seckin Citak, Takane Hori: Many Case Simulation for Estimating Urban Earthquake Disaster Accounting Uncertainties in Structure Models, Computational Engineering and Science for Safety and Environmental Problems (COMPSAFE 2014), 13-16 April 2014.

(3) Invited Talks

1. Jian Chen, Hideyuki O-tani, Kohei Fujita and Muneo Hori, An Application of High Performance Computing: Stability Analysis for Soil Liquefaction, Tongji University, Shanghai, Dec. 25, 2014.

(4) Posters and presentations

1. Hideyuki O-TANI, Jian CHEN and Muneo HORI: Template-Based Automatic Construction of Building Models from GIS data, COMPSAFE 2014, Sendai, 16, April 2014.
2. Hideyuki O-TANI, Jian CHEN and Muneo HORI: Association between 3D Shapes and Attributes Contained in Two Different Types of GIS Data, JSCE symposium on applied mechanics, Okinawa, Japan, 11, May 2014.
3. Hideyuki O-TANI, Jian CHEN and Muneo HORI: Automatic Construction of Urban Model for Disaster Simulation from Urban 3D Map and Official Building Registry, The 14th Japan Earthquake Engineering Symposium, Chiba, Japan, 4, December 2014.
4. Jian Chen, Hideyuki O-tani and Muneo Hori, Stability Analysis for Local Liquefaction Initiation of Plane Wave Type, 14th IACMAG International Conference, Kyoto, Sep.22-25, 2014 (Oral presentation).
5. Jian Chen, Hideyuki O-tani and Muneo Hori, Stability Analysis of Liquefaction Considering Soil-Water Coupling, The 5th AICS International Symposium, Kobe, Dec 08-09, 2014 (Poster presentation).
6. Jian Chen, Hideyuki O-tani and Muneo Hori, Stability Analysis of Liquefaction Considering Soil-Water Coupling, 2015 Symposium on the Application of Mechanics to Geophysics,

San Diego, Jan.17-18, 2015 (Poster presentation).

7. Jian Chen, Hideyuki O-tani and Muneo Hori, Stability Analysis of Wave Propagation for Investigation of Triggering Conditions of Liquefaction, COMPSAFE2014, Sendai, Apr.13-16, 2014 (Oral presentation).
8. Jian Chen, Hideyuki O-tani and Muneo Hori, On Mathematical Stability Analysis of Liquefaction Considering Soil-Water Coupling, 17th Applied Mechanics Symposium, JSCE, Naha, May 10-11, 2014 (Poster presentation).

(5) Patents and Deliverables