High resolution tsunami simulation in urban areas using detailed city model and three dimensional fluid analysis methods

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SUMMARY:
In this paper, we perform high resolution tsunami simulation using three-dimensional fluid analysis methods. We employ Smoothed Particle Hydrodynamics (SPH) for fluid analysis. The fluid analysis code is parallelized using distributed memory type parallelization methods. For application to real city terrains, we make input city models from data stored in the Geographic Information System (GIS). The city modeling method is made so that it can reflect the damage of structures caused by strong ground motion on tsunami simulation. Application shows that the flow of tsunami changes when considering the damage of structures due to strong ground motion.

Keywords: high resolution tsunami simulation, city modeling methods, smoothed particle hydrodynamics

1. INTRODUCTION

Tsunami simulations using physics-based numerical analysis methods with city models that reflect properties of a real city are used to estimate the consequences of tsunami hazards. Tsunami simulations widely used at present employ two-dimensional shallow water equations aiming to compute the inundation area. The 2004 Indian Ocean Earthquake and 2011 Tohoku Earthquake have triggered large tsunamis that caused destruction of buildings and flow of structural debris; it is important to simulate these phenomena in addition to the inundation area. To simulate such phenomena, three-dimensional analysis methods that can analyze fluid-structure interaction and failure of structures are needed. Damage of structures before tsunami loading might affect the failure of structures. Thus, it is also important to simulate the damage of structures by strong ground motion and reflect it to the latter tsunami simulation. As a step towards such a detailed simulation, we aim to perform tsunami simulation using three-dimensional fluid analysis in high resolution, with methods that reflect damage of structures due to strong ground motion to tsunami flow.

For fluid analysis, we use particle based methods, which are able to analyze complex free surface flows, such as wave breaking or splitting and merging at corners of buildings. Here, we use Smoothed Particle Hydrodynamics (SPH). Since three-dimensional simulation in high resolution becomes large in scale, we use distributed memory type parallelization methods for parallelization of the fluid analysis code.

In order to perform such a simulation targeted on a real city, detailed city models that reflect the shapes of buildings and ground elevation, etc. are needed. The input city model for a high resolution simulation becomes large; we need an automatic city modeling method that uses data stored in the Geographic Information System (GIS) as an input. To utilize available GIS datasets in different formats, the city modeling method needs to be extendible, with robustness for application to large datasets. We develop an extendible and robust method that generates a city model automatically from GIS data.

Several studies on tsunami simulation using three dimensional fluid analysis methods are found in the literature; for example, see Yasuda and Hiraishi (2004), Asai et al. (2009) and Harada et al. (2012). Studies by Yasuda and Hiraishi (2004) model the city terrain consisting of building shape and ground elevation using GIS and Computer Aided Design (CAD) data, and simulate the inundation flow using three-dimensional fluid analysis methods. Studies by Asai et al. (2009) and Harada et al. (2012) model the city terrain using GIS data and compute the tsunami flow using the SPH method. Compared with these methods, our method can be applied to a wide variety of areas by using an extendible and automatic city modeling method. This feature enables us to couple Seismic Response Analysis (SRA) of structures to reflect the earthquake induced damage of structures on tsunami simulation.

As an illustrative example of the developed method, we perform tsunami simulation targeted on the coastal area of Sendai, Japan, which is one of the severely hit areas in the 2011 Tohoku Earthquake. We compare the results of tsunami simulation both with and without considering the damage of structures due to strong ground motion.

2. METHODOLOGY

2.1. Fluid Analysis

2.1.1. Smoothed particle hydrodynamics

We use the weakly compressible SPH, which models an incompressible flow as a weakly compressible flow and use explicit time integration; see works by Monaghan (1994) for details. In SPH, fluids are modeled using fluid particles, and boundaries are modeled as boundary particles that are aligned to make a surface. In the following paragraphs, we briefly summarize the SPH method used in this study; see Fujita et al. (2011) for further details.

SPH discretizes a function using particles as

$$f^a = \sum_b f^b W\left(\boldsymbol{x}^a - \boldsymbol{x}^b, h\right)\frac{m^b}{\rho^b}, \tag{2.1}$$

where $W(.)$ is a smoothing function, h is the smoothing length, f^a is the discretized value of $f(\boldsymbol{x})$ at particle a, and $\{\boldsymbol{x}^a, m^a, \rho^a\}$ are the position, mass and density of particle a. We use the cubic spline for the smoothing function. Using Eqn. (2.1), we discretize the Navier-Stokes equation,

$$\frac{Dv_i}{Dt} = -\frac{1}{\rho}\frac{\partial p}{\partial x_i} + g_i + \upsilon\frac{\partial v_i}{\partial {x_j}^2}, \tag{2.2}$$

as

$$\begin{aligned} \frac{\mathrm{d}v_i}{\mathrm{d}t} &= -\sum_b m^b\left(\frac{p^a}{\left(\rho^a\right)^2} + \frac{p^b}{\left(\rho^b\right)^2}\right)W_{,i}\left(\boldsymbol{x}\right)\Big|_{\boldsymbol{x}=\boldsymbol{x}^b-\boldsymbol{x}^a} \\ &+ g_i + \sum_b m^b \frac{4\upsilon\left(v_j^b - v_j^a\right)W_{,j}\left(\boldsymbol{x}\right)\Big|_{\boldsymbol{x}=\boldsymbol{x}^b-\boldsymbol{x}^a}}{\left(\rho^a+\rho^b\right)\left|\boldsymbol{x}^b-\boldsymbol{x}^a\right|^2}\left(v_i^b - v_i^a\right) \end{aligned}, \tag{2.3}$$

where D/Dt is the Lagrangian differentiator, $\{\boldsymbol{v}, p, \boldsymbol{g}, \upsilon\}$ is velocity, pressure, gravitational acceleration, and viscosity. $(.)_{,i}$ is partial differentiation $\partial(.)/\partial x_i$. Here, we used the method by Lo and Shao (2002) for computation of viscous terms. The continuity equation,

$$\frac{\partial \rho}{\partial t} = -\rho \frac{\partial v_i}{\partial x_i}, \tag{2.4}$$

is discretized as

$$\frac{\mathrm{d}\rho^a}{\mathrm{d}t} = \sum_b m^b \left(v_i^b - v_i^a\right) W_{,i}(\boldsymbol{x})\Big|_{\boldsymbol{x}=\boldsymbol{x}^b-\boldsymbol{x}^a} . \tag{2.5}$$

Since the weakly compressible assumption leads to an additional variable ρ, we assume pressure as a function of density;

$$p(\rho) = \frac{c_0^{\ 2}\rho_0}{\gamma}\left\{\left(\frac{\rho}{\rho_0}\right)^{\gamma} - 1\right\}, \tag{2.6}$$

where c_0 is a constant that is set to 10 times the maximum velocity during the simulation; $c_0 = 10 \max|\boldsymbol{v}|$, ρ_0 is the reference density and γ is a constant that takes value of 7. See Monaghan and Kos (1999) for details of Eqn. (2.6). Using Eqns. (2.3), (2.5) and (2.6), we perform explicit time integration using the predictor-corrector method and X-SPH correction. See Monaghan (1989) for details of X-SPH correction. The inputs of SPH code are the position and velocity of fluid particles and boundary particles, and the outputs are the time history of fluid position, velocity, and pressure.

2.1.2. Implementation and parallelization of SPH code

The fluid analysis code is parallelized by partitioning the domain using the k-d tree and assigning each sub-domain to a core so that each core has nearly equal number of fluid particles. Assuming that the variance of the distribution of fluid particles in the *z* (vertical) direction is small compared with the variance in the *x* or *y* (horizontal) directions, we perform the k-d tree decomposition in two-dimensions; in the *x*-*y* plane. Necessary information (particle position, velocity, pressure and density) at boundaries of sub-domains is communicated among the cores to perform a parallel computation. Fluid particles move between the sub-domains as the tsunami proceeds; we repartition the target domain when the number of fluid particles in each domain becomes unbalanced.

2.2. City Modeling Method

Since each GIS dataset and input city model for each simulation has different formats (e.g. vector or raster, ASCII or binary, structured or unstructured), we need data conversion between each dataset and simulation. To utilize multiple GIS datasets and multiple simulations, data conversion modules must be extendible, and also robust for application to large datasets. In this study, we convert GIS data to input city models for simulations via Common City Data (CCD); see Fig. 2.1. CCD is a dataset of a city in a common data format that can be accessed from each of the component simulations. We first convert GIS data to CCD. Next, we convert relevant parts of CCD to input city models for each component simulation. After performing analysis on the input city models, the results are analyzed and written back to CCD. By using CCD, we can utilize multiple GIS datasets and multiple component simulations with a few data conversion modules, which are shown as arrows in Fig. 2.1.

To store various types of data, CCD is stored in SHAPE and GRID formats. The SHAPE format consists of nodes and connectivity information, while the GRID format stores data in a structured grid format. The SHAPE format can be used to store vector type data while the GRID format can be used to store raster type data of GIS.

Using this method, we integrate seismic response analysis of structures and tsunami simulation, so that the damage of structures by strong ground motion is reflected on the latter tsunami simulation. We describe the seismic response analysis component in Appendix A and the integration method in detail in Appendix B.

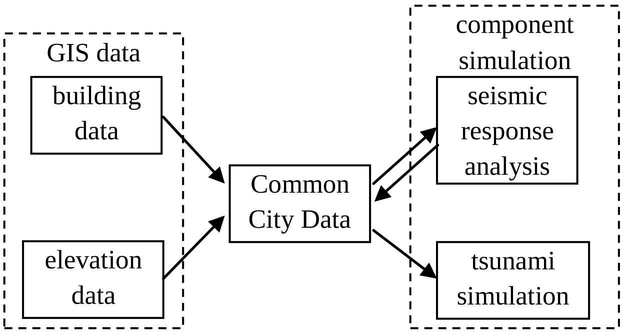

Figure 2.1. Integration of simulations using Common City Data

3. APPLICATION

As an application of the developed method, we apply it to a coastal area of Sendai, Japan. The computation is performed on a cluster with 24 computation nodes each with dual hexa-core Intel Xeon X5680 (3.33GHz) CPUs and 48GB DDR3 memory connected with a QLogic 12200 InfiniBand Switch.

We first convert GIS data of buildings and ground elevation to CCD. Fig. 3.1 shows the overview and details of the constructed city model. The elevation is modeled in resolution of 1m, and building shapes are modeled as polygons.

Next, CCD is converted to input city model for SRA, and SRA is performed using strong ground motion observed in the 2011 Tohoku Earthquake (K-NET MYG013, Sendai). The 0.01s x 30,000 = 300s simulation took 61 minutes using 24 cores. Figs. 3.2 and 3.3 show some of the snapshots of the results. Colors indicate the deformation, and deformation is magnified by 20 times. We can see that each building has different response in accordance with its height and shape.

Based on the results of SRA, we assume that a structure will collapse if its maximum drift angle is larger than threshold r_0 = 1/50, and deform shapes of structures in CCD accordingly. The left figure in Fig. 3.4 shows the maximum drift angle, and the right figure in Fig. 3.4 shows the modified city model. We can see that some of the structures facing the coast have collapsed and the width of roads facing the collapsed buildings is narrowed.

We perform tsunami simulation on the original and modified city models. We simulate a domain of 1,000 x 800m in resolution of 1m using the properties summarized in Table 3.1. The input tsunami is a block of water 12m in height with initial velocity of 5m/s shown in blue in Fig. 3.5. The 0.001s x 50,000 = 50s simulation took 51 hours using 64 cores. Figs. 3.6 and 3.7 show some of the snapshots of the results. We can see that the flow of tsunami changes in accordance with the change in the city terrain.

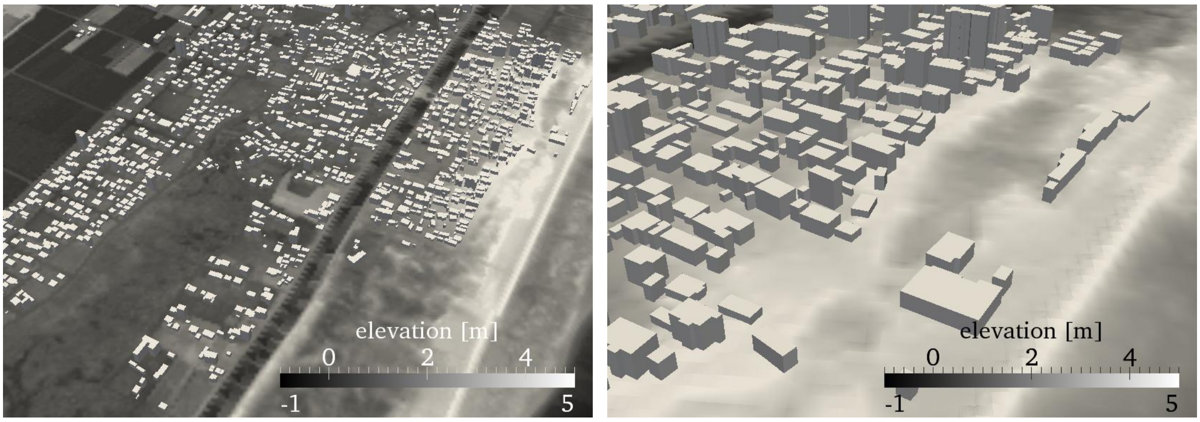

Figure 3.1. Overview and close up view of city model. Elevation and building shape are modeled.

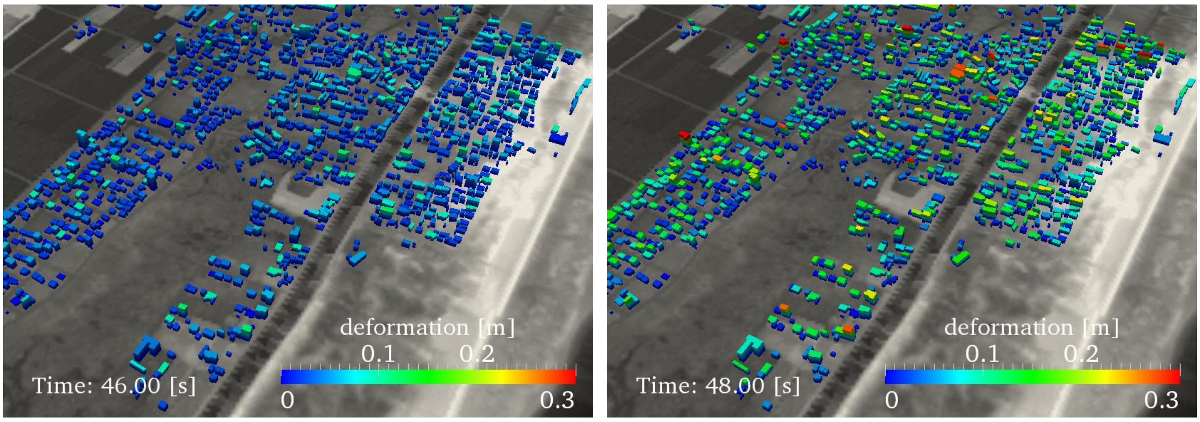

Figure 3.2. Overview of seismic response analysis results. Colors indicate magnitude of deformation.

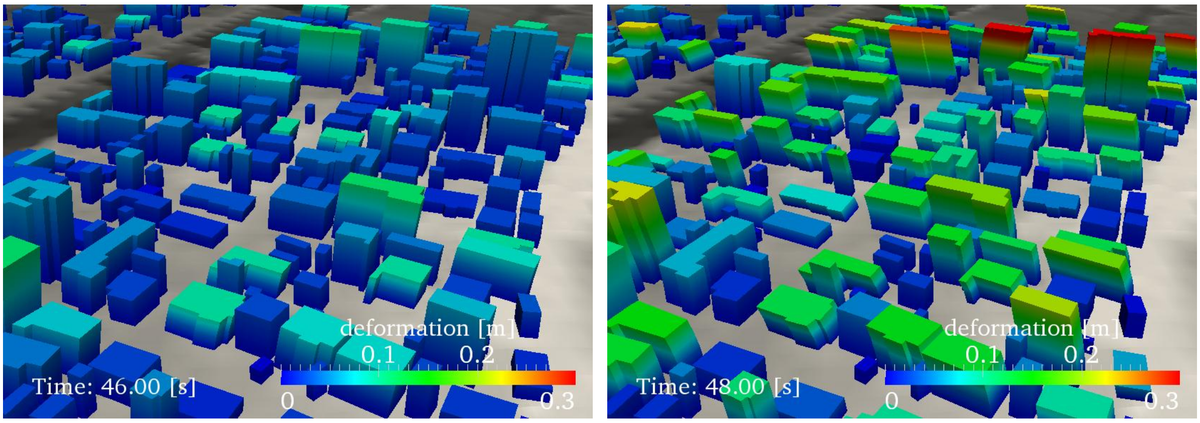

Figure 3.3. Close up view of seismic response analysis results. Colors indicate magnitude of deformation. Deformation is magnified by 20 times.

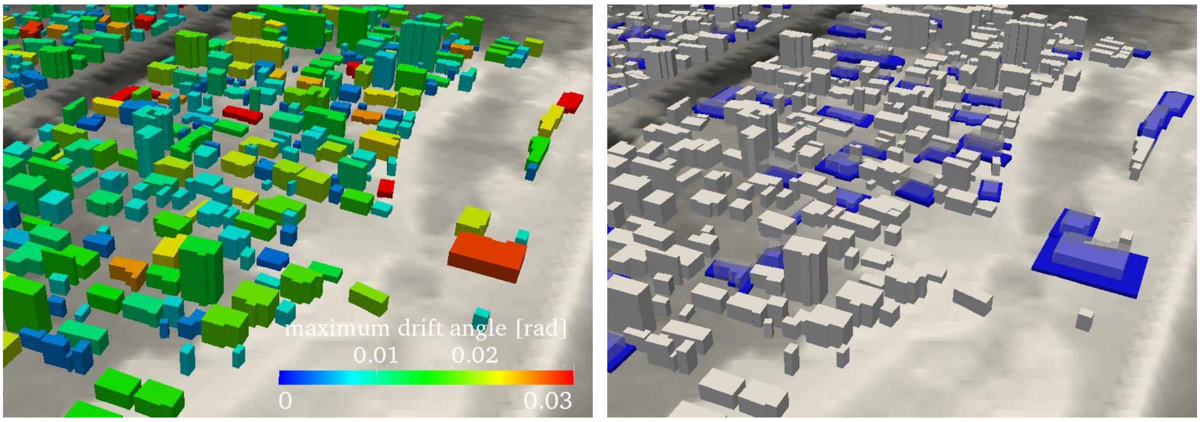

Figure 3.4. Modification of city model based on SRA results. Left: maximum drift angle of buildings. Right: modified city model, blue indicate collapsed shape of buildings, where transparent indicate the original shape.

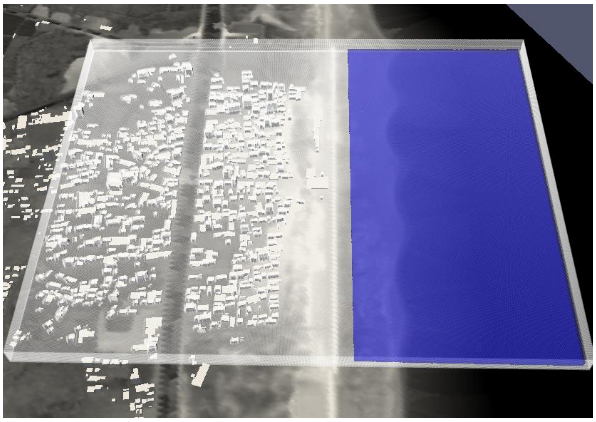

Figure 3.5. Analysis domain of tsunami simulation. Blue indicates the input tsunami wave.

Table 3.1. Settings of tsunami simulation

fluid properties	density	1.0 x 10^3 kg/m^3
	viscosity	1.0 x 10^{-6} m^2/s
number of particles	fluid	3,694,981
	boundary (case1)	2,218,985
	boundary (case2)	2,180,451

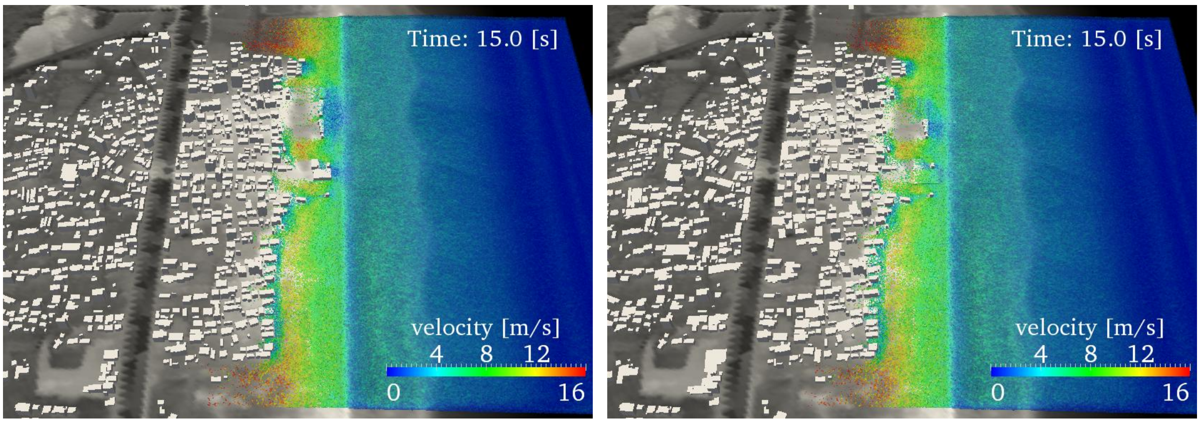

Figure 3.6. Overview of results of tsunami simulation. Colors indicate fluid velocity. Left: tsunami simulation results without regarding, right: with regarding structural damage due to strong ground motion.

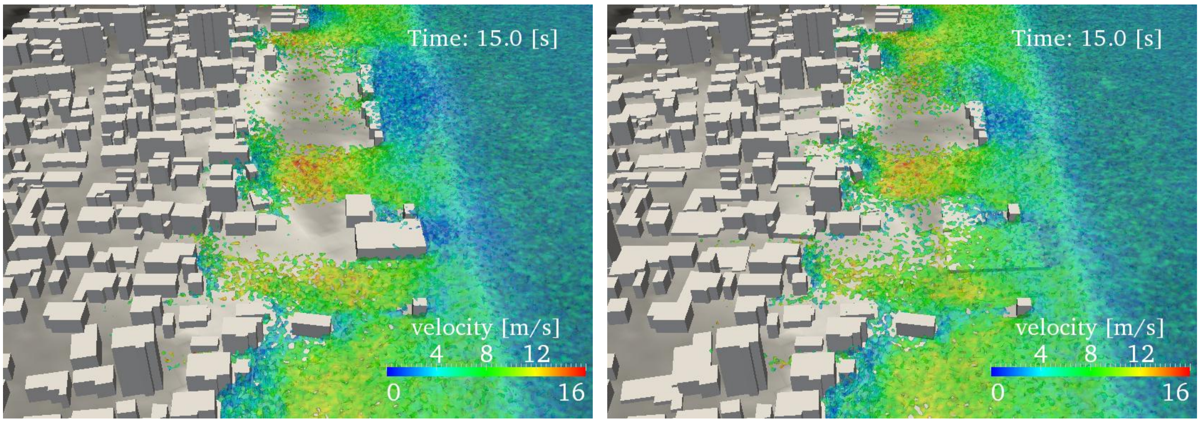

Figure 3.7. Close up view of results of tsunami simulation. Colors indicate fluid velocity. Left: tsunami simulation results without regarding, right: with regarding structural damage due to strong ground motion.

4. CLOSING REMARKS

In this study, we performed tsunami simulation using three-dimensional fluid analysis in high resolution. Here, we implemented standard fluid analysis methods and distributed memory type parallelization methods in the tsunami simulation code. We have also developed a city modeling method to make inputs of the tsunami simulation from data stored in GIS. We made this method extendible so that multiple types of GIS data and disaster simulations can be used. Using the developed method, we performed tsunami simulation that reflects the damage of structures due to strong ground motion based on seismic response analysis of structures.

In the future, we plan to develop fluid-structure interaction methods capable of fracture analysis to simulate destruction of buildings due to tsunami loading. We also plan to improve the parameters used in generation of structure skeletons for obtaining reasonable results in SRA.

APPENDIX A. SEISMIC RESPONSE ANALYSIS

We use the One Component Model (OCM), which models Reinforced Concrete (RC) structures as skeletons consisting of beams and columns with floor mass for SRA. See Giberson (1967) for details of OCM. Beams are modeled with bending and shear springs, while columns are modeled with bending, axial and shear springs. The Takeda model is used to model the hysteresis of shear springs of beams and columns. See Takeda et al. (1970) for details of the hysteresis model. We use a distributed memory type parallel code for computation of a large number of structures; see works by Maddegedara and Hori (2011) for details. The inputs of SRA are the floor mass, properties (stiffness, strength, and hysteresis parameters) and connectivity of beams and columns for each structure, and input strong ground motion. The output of SRA is the time history of deflection at each floor.

APPENDIX B. INTEGRATING SIMULATIONS USING COMMON CITY DATA

In this section we explain the details of each conversion module used to perform a seamless simulation of earthquake and tsunami disaster in an urban area.

B.1. Converting GIS Data to CCD

SRA needs the properties of buildings while tsunami simulation needs the shape of a city to perform simulations. In this study, we use a two-dimensional vector GIS data that stores the external shapes of buildings and a Digital Elevation Map (DEM) as inputs. We make a module that converts the vector building data to SHAPE format, and another module that converts DEM data to GRID format; see arrows (i) and (ii) in Fig. B.1. Since the two-dimensional GIS data does not have the height of buildings, we guess it using the area of a building based on statistical data. The DEM is interpolated using bilinear functions to increase the resolution from 5m to 1m.

B.2. Converting CCD to City Models for Seismic Response Analysis

We convert the external shape data of buildings in CCD to input structure skeletons for SRA, corresponding to arrow (iii) in Fig. B.1. Since the structural properties are not included in the GIS dataset, we generate it based on the building design code for RC structures in Japan. We first guess the layout of structural members based on the buildings floor configuration and height. Based on the number of stories and area, the properties (stiffness, strength, and hysteresis parameters) of springs that model beams and columns are set so that the building satisfies the building design code. This module is in the development stage and the validity of the generated skeleton has not been checked. We plan to do this in our future works for reliable results of SRA.

B.3. Using Results of Seismic Response Analysis to Modify CCD

The results of SRA are used to modify CCD by assuming a condition for a structure to collapse and modifying its shape accordingly. As the simplest method, we assume that a structure will collapse if the maximum drift angle (r = max $|u|$ / h, u: deformation, h: height of a building) is larger than a threshold r_0. We modify the building shape by making its height 1/4 and expanding its shape by 3/2 times in the horizontal directions. The modified shapes of buildings are updated in CCD; see arrow (iv) in Fig. B.1.

B.4. Converting CCD to City Models for High Resolution Tsunami Simulation

Using the building shape data and elevation data in CCD, input city model for tsunami simulation is made. We first convert the building data in SHAPE format to GRID format using the Scanline Floodfill Algorithm; see arrow (v) in Fig. B.1. The building and elevation GRID data can be easily converted to the input city model for tsunami simulation by placing particles on the vertices of the structured grid; see arrow (vi) in Fig. B.1. The converted city model expresses the city terrain by boundary particles aligned in resolution of 1m. We do not reflect the results of tsunami simulation back to CCD, although we plan to do this in the future using a fluid-structure interaction method.

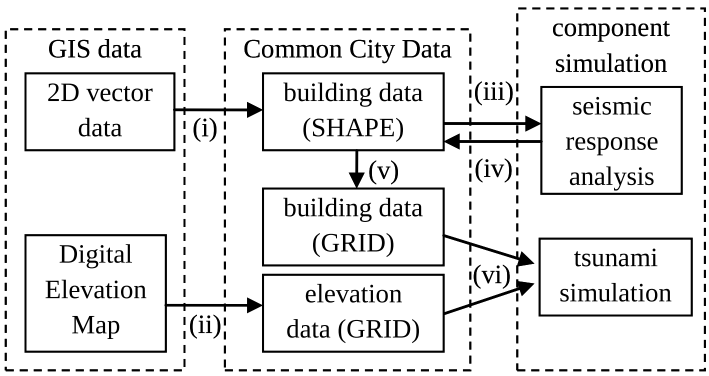

Figure B.1. Integration of simulations using Common City Data, in detail.

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REFERENCES

Fujita, K., Ichimura, T., Hori, M., Wijerathne, M. L. L. and Tanaka, S. (2011). Conversion of GIS data to city model for particle based high resolution tsunami simulation. *Journal of Japan Society of Civil Engineers*. (in press, in Japanese with English abstract)

Giberson, M. F. (1967). The response of nonlinear multi-story structures subjected to earthquake excitation. Earthquake Research Laboratory, California Institute of Technology, Pasadena, CA, EERL Report.

Lo, E.Y.M. and Shao, S. (2002). Simulation of near-shore solitary wave mechanics by an incompressible SPH method. *Applied Ocean Research*. **24**, 275-286.

Monaghan, J. J. (1989). On the problem of penetration in particle methods. *Journal of Compuational Physics*. **82:1**, 1-15.

Monaghan, J. J. (1994). Simulating free surface flows with SPH. *Journal of Compuational Physics*. **110**, 399-406.

Monaghan, J. J. and Kos, A. (1999). Solitary Waves on a Cretan Beach, *Journal of Waterway, Port, Coastal and Ocean Engineering*, May/June 1999, 145-154.

Sobhaninejad, G., Hori, M. and Kabeyasawa, T. (2011). Enhancing integrated earthquake simulation with high performance computing. *Advances in Engineering Software*. **42:5**, 286-292.

Takeda, T., Sozen, M. A. and Nielsen, N., N. (1970). Reinforced Concrete Response to Simulated Earthquakes. *Journal of the Structural Division*. **96:12**, 2557-2573.

Yasuda, T. And Hiraishi, T. (2004). Highly Accurate Inundation Simulation by MARS Method on Compound Coastal Urban Area. *Report of the Port and Airport Research Institute*. **43:2**, 1-32. (in Japanese with English abstract)

Architectural Institute of Japan (1988). Standard for Structural Calculation for Reinforced Concrete Structures, Architectural Institute of Japan. (in Japanese)

Hori, M. (2011). Introduction to Computational Earthquake Engineering (2nd Edition), Imperial College Press.

Asai, M., Hayashi, T., Sugi, T., Sonoda, Y. and Sakai,Y. (2009). Geometrical modeling of coastal area with numerical map and its fluid simulation by a SPH particle method. *The 14th JSCES annual conference*. (in Japanese)

Harada, Y., Kashiyama, K. and Asai, M. (2012). Application of a stabilized incompressible SPH method to Tsunami wave analysis. *The 16th National Congress of Theoretical and Applied Mechanics*. OS17-06. (in Japanese with English abstract)

Maddegedara, L. and Hori, M. (2011). Application of high performance computation for the prediction of urban area earthquake disaster, *IESL-SSMS Joint International Symoposium on Social Management Systems 2011*. SMS11-4706.

Kyoshin Network (K-NET), National Research Institute for Earth Science and Disaster Prevention, http://www.k-net.bosai.go.jp/k-net/

Vandevenne, L. (2007). Scanline Floodfill Algorithm With Stack (floodFillScanlineStack), http://lodev.org/cgtutor/floodfill.html