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APPLICATON OF SEAMLESS SIMULATION OF SEISMIC RESPONSE ANALYSIS AND HIGH RESOLUTION TSUNAMI SIMULATION TO COASTAL AREA OF SENDAI

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ABSTRACT: We perform a seamless simulation of Seismic Response Analysis (SRA) of structures and High Resolution Tsunami Simulation (HRTS) to estimate the overall damage of a city under earthquake-tsunami hazard scenarios. We use a Common City Model (CCM) converted from data stored in the geographic information system as inputs of both simulations. Results of SRA are reflected to HRTS by modifying the shape of structures if it is assumed to be collapsed. Application to coastal area of Sendai shows that the tsunami flow changes according to the changes in CCM based on results of SRA.

Key Words: Integrated Natural Disaster Simulation, Seismic Response Analysis, High Resolution Tsunami Simulation, Common City Model

INTRODUCTION

The 2011 Tohoku earthquake caused Strong Ground Motion (SGM) and tsunami in coastal areas of northeastern Japan, leading to a large number of fatalities and serious damage in coastal urban areas. The Tokai, Tonankai, or Nankai earthquakes expected in southwestern Japan can cause a series of severe earthquake and tsunami hazards in coastal areas. To make appropriate mitigation strategies, estimation of disasters under hazard scenarios with a series of hazards is needed.

As a candidate to simulate the overall damage of urban areas under natural disaster scenarios, the authors have been developing an Integrated Natural Disaster Simulator (INDS); for example, see (Hori et al. 2008) and (Sobhaninejad et al. 2011). INDS is an integration of component simulations, simulating each phase of an urban disaster. Each component simulation uses physics-based computational methods with input city models that reflect the actual properties of a city, constructed from data stored in the Geographic Information System (GIS). In the past, the main development of INDS was targeted on earthquake disasters (Integrated Earthquake Simulator, IES). IES integrates seismic wave propagation analysis from the fault to city, Seismic Response Analysis (SRA) of structures using the computed SGM, and simulation of evacuation processes using Multi Agent Simulation.

In this paper, we integrate SRA and High Resolution Tsunami Simulation (HRTS). We aim to simulate damage and collapse of structures, since it is essential to ensure human life space. For SRA, we use non-linear structural analysis methods on each structure in the target area. For tsunami simulation, we use HRTS, which is a tsunami simulation using a three-dimensional analysis method aimed to analyze destruction of structures and collapse of structures due to tsunami loading. Since such a tsunami analysis code is unavailable to the authors, we develop a code using standard computational fluid analysis methods and distributed memory type parallelization methods.

We perform a seamless simulation of SRA and HRTS by exchanging information between simulations. We exchange information via Common City Model (CCM), which is a common data set of spatial and temporal properties of a city, accessible from each component simulation. Here, we develop data conversion modules that convert data stored in GIS to CCM, and data conversion modules that exchange information between component simulations and CCM.

As an application of the developed method, we conduct a simulation targeted on the coastal area of Sendai. We convert external shapes of structures and ground elevation data stored in GIS to CCM, and make input structure dataset for SRA. We assume a criterion for a structure to collapse, and modify the structural shapes in CCM based on the results of SRA. We compare the results of HRTS run on the modified and original city configuration to confirm that we can run a seamless simulation that could be used to evaluate the overall damage of a city under a series of earthquake and tsunami hazards.

METHODOLOGY

In this section, we explain about the framework developed to perform a seamless simulation of SRA and HRTS. In order to make an extendible method to accommodate multiple GIS data and component simulations, we use CCM. CCM is a common data set that stores the properties of a city in common data format. We first convert data stored in GIS to CCM. Then, each component simulation reads relevant parts of CCM and makes an input city model, analyzes and writes the modifications to the city model back to CCM; see Fig.1. By using a common data set of a city, we can integrate simulations without the hassle to make direct data conversion modules between each component simulation. The following are the details of the conversion methods and analysis methods used in this paper.

We convert elevation and structure data stored in GIS to CCM. Here, we develop modules that convert Digital Elevation Map (DEM) and two-dimensional vector structure data to CCM; see arrow (i) and (ii) in Fig. 1.

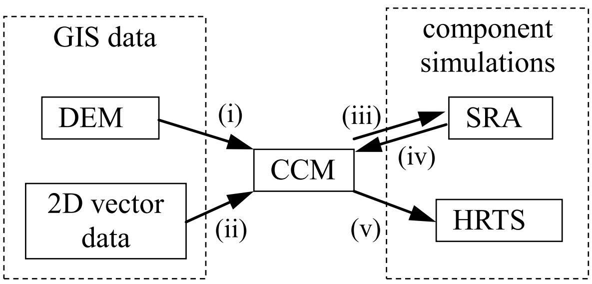

Fig. 1 Design of INDS using CCM

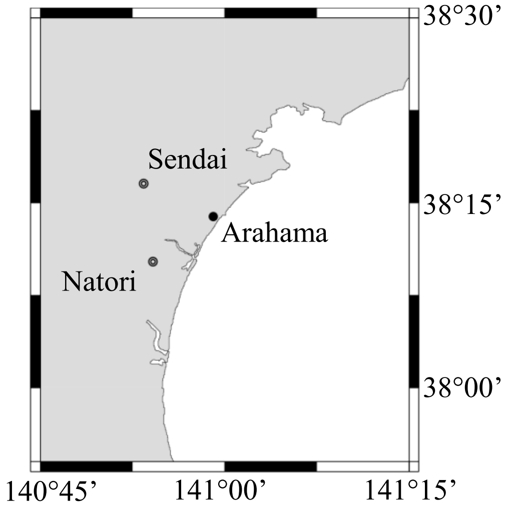

Fig. 2 Target area. Arahama, Wakabayashi ward, Sendai city, Japan.

The inputs of SRA are the shape of structures and input SGM. We convert structure shape data in CCM to inputs of SRA; see arrow (iii) in Fig.1. Since properties of structural members are not available in GIS, we guess the material properties and configuration of structural members using the external shape of structures based on the design code of Japan. SRA is performed using a pre-developed code using One Component Model (OCM). OCM is a non-linear structural analysis method designed for analysis of RC structures. The output of SRA is the time series of displacement of structures. We assume a criterion for a structure to collapse and change the CCM according to SRA results; see arrow (iv) in Fig.1. For simplicity, we assume that a structure will collapse if the maximum drift angle

$$R = \max|u|/h, \tag{1}$$

is larger than a threshold R_0. Here, $\max|u|$ is the maximum displacement during the simulation and h is the height of a structure. We modify the shape of a structure by making the height 1/4 and spreading the structure 1.5 times in the horizontal directions if a structure is determined to be collapsed.

The inputs of HRTS are the external shapes of structures and ground elevation, and input tsunami wave. We convert the structure and ground elevation data in CCM for HRTS; see arrow (v) in Fig.1. We use a distributed memory type parallel analysis program using Smoothed Particle Hydrodynamics (SPH) for fluid analysis; see (Monaghan 1994) for details of SPH. The output of HRTS is a time series of fluid position, velocity and pressure. We do not change the configuration of the city based on HRTS, although we plan to do this in the future using a fluid-structure interaction method.

APPLICATION TO COASTAL AREA OF SENDAI CITY

We apply the developed method to Arahama, Wakabayashi ward, Sendai, Japan, which is one of the severely hit areas by the tsunami in the 2011 Tohoku earthquake; see Fig. 2. The objectives of this section is to check that a seamless simulation of SRA and HRTS can be run on GIS datasets for estimation of overall damage in coastal areas under earthquake-tsunami disasters.

We first convert data stored in GIS to CCM. The target area is a 2.0 x 3.0km domain with 1416 structures. CCM consists of ground elevation and external shapes of structures; see Fig. 3. Here, GIS data provided by the Geospatial Information Authority of Japan and NTT Geospace Corporation is used as an input.

We make an input city model for SRA and excite structures using SGM observed at K-NET MYG013 station (Sendai) in the 2011 off the Pacific coast of Tohoku earthquake. For simplicity, we

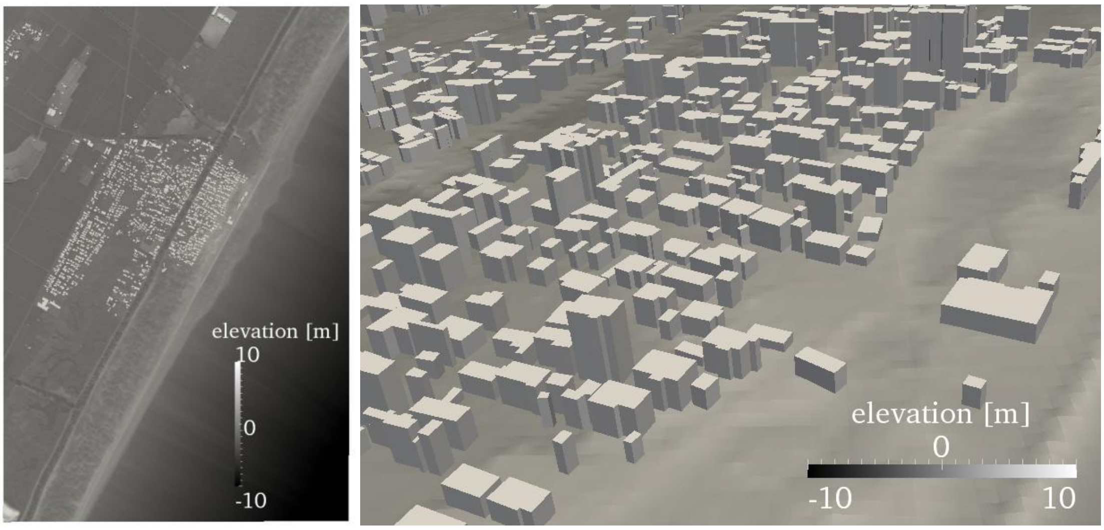

Fig. 3 Constructed CCM, consisting of external shape of structures and ground elevation. GIS data provided by Geospatial Information Authority of Japan and NTT Geospace Corporation is used.

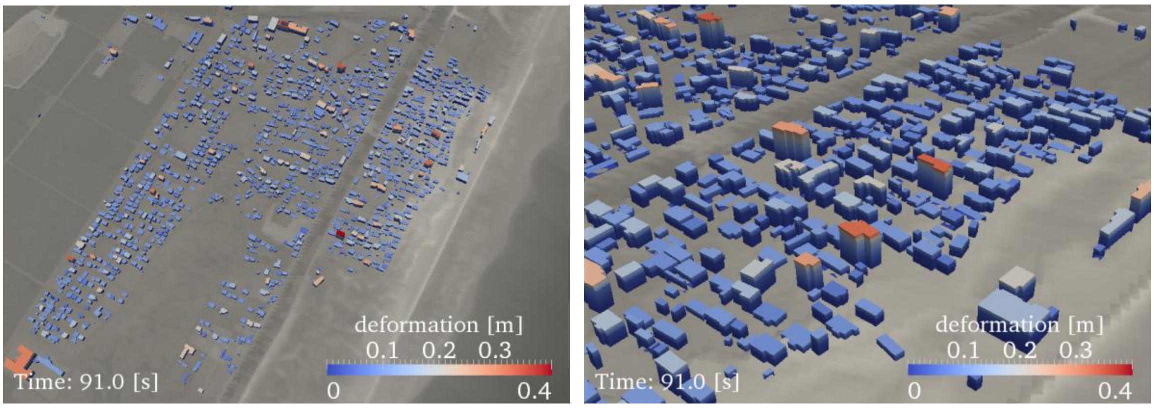

Fig. 4 Results of SRA at t = 91.0s from start of simulation. Colors indicate magnitude of deformation. Response of each structure under SGM observed in the 2011 Tohoku region earthquake is analyzed.

input the same SGM to the base of each structure. The simulation is 0.01s x 30,000steps = 300s. Fig. 4 shows snapshots at t = 91.0s after start of the simulation. From this figure we can see that structures have different response to the same input SGM according to its height, shape, and directions.

We deform structures by assuming that a structure will collapse if the maximum deformation angle defined in Eq. (1) is larger than a threshold R_0 = 1/40. We set this threshold relatively small compared to the real estimate for a structure to collapse so that a number of structures will collapse; we do this to have a clear difference between the modified and original city models. Fig. 5 shows the deformed state of the city, where blue indicates collapsed shape, transparent indicates original shape, and solid white indicate shapes of structures that are not determined to be collapsed.

Two cases of HRTS are performed; case 1 is with the modification of structures based on SRA, and case 2 is the original CCM without modifications. We conduct HRTS on a 1,000 x 800m area, each discretized in resolution of 1m. We input tsunami wave using a block of water 12m in height with initial velocity of 5m/s; see Fig. 6. Although this setting is quite different from the actual tsunami wave that hit this area, it is enough to confirm that the HRTS is applicable to a real city dataset stored in GIS. We plan to use computed tsunami waves from the source to bay area as input tsunami waves in the future. The number of boundary particles used to model elevation and structure shapes for the 2 cases

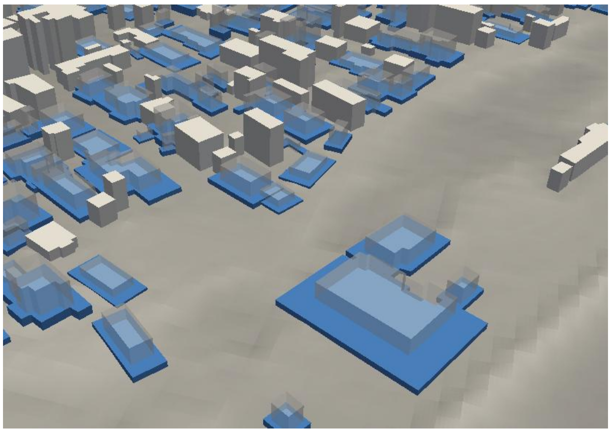

Fig. 5 Modified city model based on results of SRA. Blue indicate shape of structures that are determined to be collapsed, transparent shape indicate original shape, and solid white indicate shapes of structures that are not determined to be collapsed.

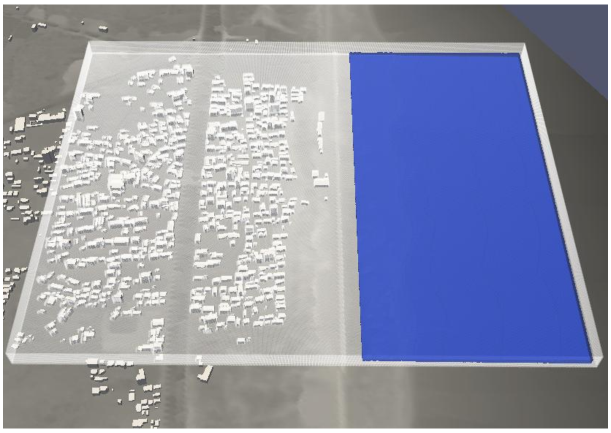

Fig. 6 Simulation setting of HRTS. Domain size of 1000 x 800m is discretized in resolution of 1m, and input tsunami wave (12m in height, initial velocity 5m/s), indicated in blue, is inputted from the coast.

are 2,120,399 and 2,218,985, respectively, while the number of fluid particles used to model the tsunami is 3,694,981 for both of the cases. The simulation is 0.001s x 40,000steps = 40s. Figs. 7 and 8 show the results for the two cases. From these figures, we can see that three dimensional flows around structures are computed. Comparing these figures, we can see that flow changes according to the modification to the city configuration.

CLOSING REMARKS

In this paper, we developed a framework to integrate SRA and HRTS by using CCM. We converted data stored in the GIS to both the inputs for SRA and HRTS via CCM, and modified the city configuration based on the results of SRA. HRTS is conducted using the modified city model. Application to coastal area of Sendai shows that the flow of tsunami changes according to the modification in the CCM based on results of SRA. Our future works are to develop fluid-structure interaction methods to simulate destruction of structures under tsunami loading.

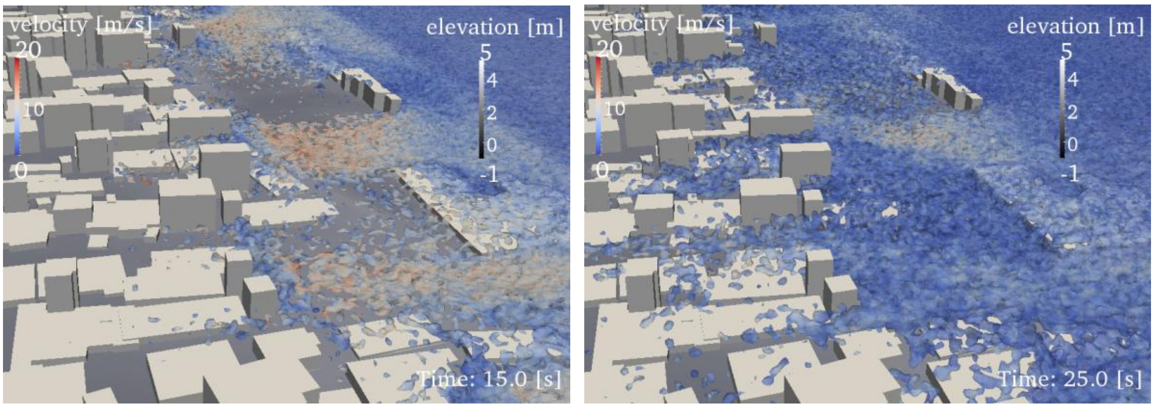

Fig. 7 Results of HRTS for case 1 (with modification to city model based on SRA results). Colors indicate fluid velocity. Left figure: t = 15s, Right figure t = 25s.

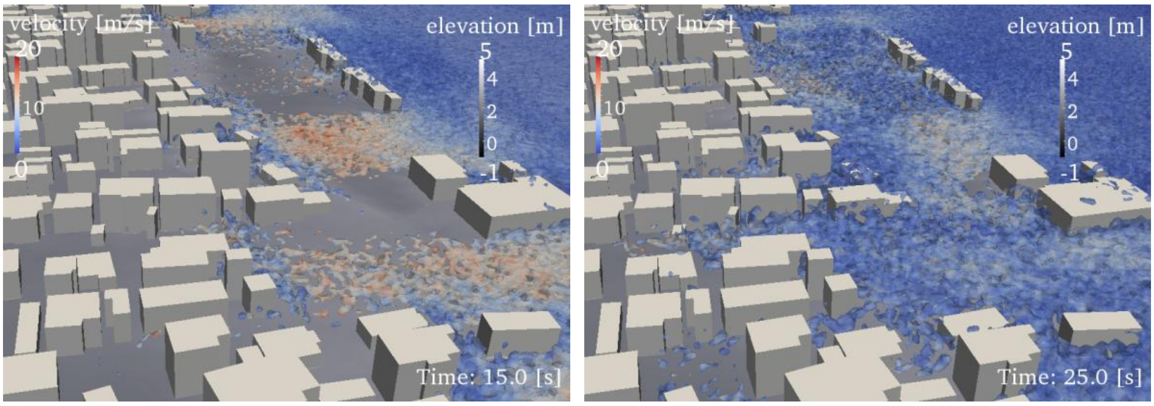

Fig. 8 Results of HRTS for case 2 (original city model). Colors indicate fluid velocity. Left figure: t = 15s, Right figure t = 25s.

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