SOIL-STRUCTURE INTERACTION ANALYSIS INTEGRATION IN AN ADVANCED APPLICATION TOOL FOR DISASTER MITIGATION

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***ABSTRACT*:** After the 2011 Great East Earthquake in Japan, various advanced application tools for structural analysis have been invented. These advanced application tools are used to investigate the dynamic response of structure and to estimate the damage of a city in any specific area under earthquake and tsunami disaster. Both the comprehension of the structural response behavior and the most damaged area in a city during a mega disaster are significantly essential for future disaster mitigation plan. However, the accuracy of structural analysis output of these advanced application tools is still a crucial issue and depends on many factors. Among these factors, soil-structure interaction (SSI) effect is regarded as an important factor for seismic response of structure under earthquake disaster. Therefore, the main objective of this paper is to integrate free field ground motion (FFGM) analysis into Object-Based Structural Analysis (OBASAN), which is an advanced computational program for structural analysis and city damage estimation. This integration allows the program to determine the ground motion amplification at the surface layer and the structure response under SSI effect. Furthermore, this integration can increase the accuracy of the output result for damaged area estimation in the target city. In this paper, element components and the architecture of OBASAN were briefly introduced. An example of FFGM analysis was presented and verified with other programs. The estimation procedure of city damage (a group of buildings) in the target area was presented at the end of this paper. The output result of FFGM analysis using OBASAN and SHAKE91 showed a good agreement for both linear and equivalent-linear analysis. This agreement confirmed that OBASAN can perform well for FFGM analysis, which facilitates performing the seismic response of structure under SSI effect and increases the accuracy of output result for city damage estimation during earthquake and tsunami disasters.

KEYWORDS: soil-structure interaction integration, earthquake and tsunami disaster mitigation

1. INTRODUCTION

The tragedy of the 2011 Great East Earthquake in Japan has left unexpected remains of the devastation of many buildings and casualties. According to National Police Agency, it has been confirmed that there were 15,891 deaths, 6,152 people injured, and 2,584 people missing across 20 prefectures [National Police Agency of Japan, 2015]. Besides this, 45,700 buildings were destroyed and 144,300 buildings were damaged under earthquake and tsunami disaster.

According to seismologists' estimation, a similar magnitude of another future earthquake can occur along the Nankai Trough in the near future, which can trigger another powerful tsunami as shown in Figure 1. These disasters can cause more devastation and casualties than the 2011 Great East Earthquake. Thus, many efforts have been made to mitigate the devastation of these inevitable disasters. These efforts include an earthquake warning system, tsunami warning system, evacuation plan, post disaster plan, structural quality strengthening, etc. Among these efforts, city damage estimation and structural quality strengthening are regarded as the most crucial and necessary factors for structural engineering.

Many advanced computational tools have been invented in order to investigate the structure response during these disasters. Moreover, these advanced application tools are being utilized to estimate the most damaged area in the city during the disasters to indicate the safety shelters for evacuation.

However, the accuracy of these advanced application tools is still the important issue that needs more efforts to solve. Among these advanced application tools, (OBASAN) [Latcharote et al., 2013] is one of the potential tools for structural analysis. OBASAN was integrated into Integrated Earthquake Simulation (IES) [Mori et al., 2006], which is utilized to estimate and visualize building response simultaneously for any target area in a city during earthquake disaster. For tsunami simulation, all buildings are modeled the same as an earthquake simulation to determine hydrodynamic force, which can be varied according to the location and arrangement of buildings. However, the accuracy of OBASAN for the damaged estimation and structural analysis are also the crucial issues.

FFGM analysis is regarded as a significant factor that facilitates performing SSI analysis, which can increase more accurate results of damaged estimation in the target city and structural response analysis compared to the reality. Therefore, the objective of this paper is to integrate the FFGM analysis into OBASAN. This integration can allow the structure to determine ground motion amplification at the surface layer and structural response under SSI effect.

In this paper, the architecture and element components of OBASAN were briefly indicated in the following section. Furthermore, the procedure of FFGM analysis was also presented. An example of FFGM analysis was conducted and results were verified with others programs. The procedure of damage estimation of a group of buildings in the target area was presented at the last section.

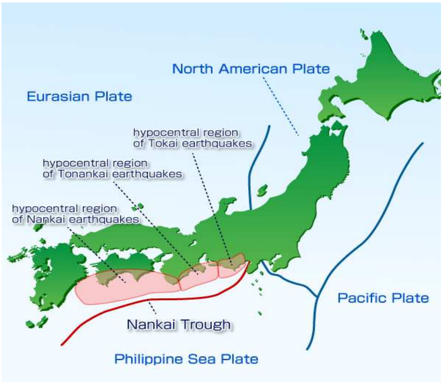


Figure 1: Earthquake zone along Nankai Trough [JAMSTEC, 2015]

2. STRUCTURAL DAMAGE EXPERIENCED FROM THE 2011 GREAT EAST EARTHQUAKE AND TSUNAMI

Structural damages experienced from the 2011 Great East Earthquake and Tsunami are very important and necessary for future design code and development of advanced computational program. According to the structural damages from the field reports, the damage can be caused by some main factors such as an earthquake, liquefaction, tsunami, debris, etc. From these forces remained unexpected damage to structures including overturned buildings, foundation, column, RC wall, and settlement of geology.

Figure 2: Overturned building, Rikuzentakata, Iwate [Kohji Tokimatsu et al., 2012]

Tsunami force is regarded as a powerful force to overturn many buildings and causes damage to wall structures in the coastal city as shown in Figures 2 and 3, while the damage of foundation and settlement of geology are mainly caused by the earthquake and liquefaction effect as shown in Figures 4 and 5. The damage of structural element in non-coastal area is induced by lateral force during an earthquake, as shown in Figure 6.

Figure 3: Damage of RC wall in Sendai, Miyagi [Kabeyasawa, T. et al, 2012]

Figure 4: Damage of pile head in Sendai, Miyagi [Masanori Iiba et al., 2012]

Figure 5: Ground settlement in Urayasu, Chiba [Kohji Tokimatsu et al., 2012]

Figure 6: Damage of column buildings in Minami Soma, Fukushima [Kabeyasawa, 2012]

Based on the field observation reports, many recommendations were proposed for further research and design implications. These recommendations included design force, structural element connection, ground amplification, interaction of soil and structure, etc. [Kabeyasawa, 2012].

According to these recommendations, SSI effect performs a significant role for structural response and damage during earthquake disaster. Moreover, the response of structure due to SSI effect under tsunami force becomes an impressive topic for further research. Therefore, the integration of FFGM in an advanced application tool was a crucial effort for further comprehension of structure response under SSI effect and damaged area estimation during the mega disaster. This comprehension can reduce a number of casualties and structural devastation in the inevitable future disasters.

3. ADVANCED APPLICATION TOOL FOR STRUCTRAL ANALYSIS (OBASAN)

OBASAN is an advanced application tool for structural analysis. OBASAN is coded in C/C++ language and divided into four main parts for structural analysis procedure: input data, computation and analysis, control system, and output data. OBASAN can perform well for nonlinear analysis of RC and steel structure. However, OBASAN is unable to perform FFGM analysis yet, which facilitates performing the response of structure under SSI effect and represent an actual response behavior of structure under an earthquake.

3.1 Architecture of OBASAN

The architecture of OBASAN is divided into eight main classes. These eight classes include CUnitValue, TransElement, Nastran, ObjectData, CFemObject, OutPutData, OutTypeData, and SystemController which constitute the process of OBASAN program as mentioned above.

3.2 Input and output data of OBASAN

In order to perform structural response analysis under static or dynamic loading, OBASAN requires input data to model structural type as indicated in Table 1. The output data is classified into four different forms including node output, element output, modal output, and hysteretic output as shown in Table 2.

Table 1 OBASAN Input Data

Input Data	Description
Node data	Node ID, DOF, coordinate, mass, rotational mass.
Element data	Element ID, element type, node number, material name.
Element Type	Spring, beam, column, macro-shell, etc.
Material	Depth, width, young modulus, shear modulus, strength, etc.
Damping	Rayleigh, Caughey, local viscous, etc.
DOF	Translation: dx,dy,dz Rotation: tyz, tzx, txy.
Load	Nodal load, surface load, etc.
Hysteretic	Bilinear, Tri-linear, Inada, Takeda, Kabeyazawa, etc.
Analysis	Newmark, Static, Differential, Frequency, etc.

Table 2 OBASAN Output Data

Output Data	Description
Node	Displacement, velocity, acceleration, etc.
Element	Stress, strain, deformation, internal force, etc.
Modal	Eigenvalue, eigenvector, period, frequency, etc.
Hysteresis	Ductility, stiffness degrading factor.

4. FREE FIELD GROUND MOTION ANALYSIS INTEGRATION

In order to perform SSI analysis, the integration of FFGM analysis into OBASAN was immensely significant. This integration allowed OBASAN to analyze the soil deposit and structure in both linear and nonlinear response behavior under earthquake and tsunami disaster.

4.1 Wave propagation motion theory

The transfer function relation of the motion amplitude from the surface of layer m to the surface of layer n is given in equation (1).

$$A_{mn}(\omega) = \frac{u_m}{u_n} = \frac{\dot{u}_m}{\dot{u}_n} = \frac{\ddot{u}_m}{\ddot{u}_n} = \frac{E_m + F_m}{E_n + F_n} \quad (1)$$

E and F are the complex function of wave motion upward and downward, respectively. The recursive formulas are shown in the following equations:

$$E_{m+1} = \frac{1}{2} E_m (1+\alpha_m^*) e^{ik_m^* h_m} + \frac{1}{2} F_m (1-\alpha_m^*) e^{-ik_m^* h_m} \quad (2)$$

$$F_{m+1} = \frac{1}{2} E_m (1-\alpha_m^*) e^{ik_m^* h_m} + \frac{1}{2} F_m (1+\alpha_m^*) e^{-ik_m^* h_m} \quad (3)$$

Where $E_1 = F_1 = 1.0$ at ground surface

$$\alpha_m^* = \frac{k_m^* G_m^*}{k_{m+1}^* G_{m+1}^*} = \sqrt{\frac{\rho_m G_m^*}{\rho_{m+1} G_{m+1}^*}}$$

$$k^{*2} = \frac{\rho\omega^2}{G^*}$$

$$G^* = G(1+2i\xi)$$

$$G = \rho V_s^2$$

k^* : complex stiffness
ρ : unit weight (kN/m3)
V_s : shear velocity (m/s)
ξ : damping ratio
h_i : depth in each layer

The shear strain and stress at depth z can be expressed in equation (4) and (5):

$$\gamma(z,t) = ik^*(Ee^{ik^*z} - Fe^{-ik^*z})e^{i\omega t} \qquad (4)$$

$$\tau(z,t) = G^*\gamma(z,t) \qquad (5)$$

Furthermore, the equivalent-linear analysis procedure in SHAKE91 was used in this integration [Idriss et al., 1992].

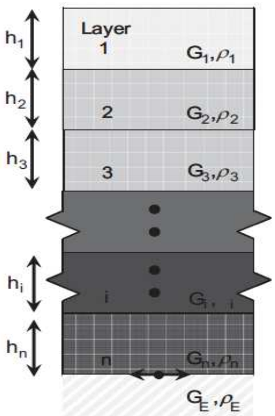


Figure 6: One-dimensional soil deposits model

4.2 Example of FFGM analysis in OBASAN

In this example, uniform soil deposit in a depth of 20m was assumed and rested on bedrock. This soil column was divided into five layers, as shown in Table 3. This analysis was performed in frequency domain (FD) and verified with results from the SHAKE91 program, which is a widely used program for FFGM analysis in FD. The input motion from the Kobe earthquake record data was applied at the base of soil column, as shown in Figure 8. The soil property in this example is the same as the property in class E of IBC code [IBC, 2006].

Table 3 soil properties for each layer

Depth (m)	$V_s(m/s)$	$\gamma(kN/m^3)$	$\xi(\%)$
0.0-3.5	180	18.1	5
3.5-7.0	180	18.1	5
7.0-10.5	180	18.1	5
10.5-15	180	18.1	5
15.0-20.0	180	18.1	5
Bedrock	550	19.3	2

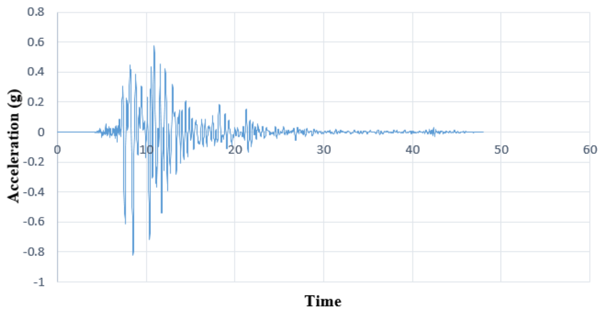
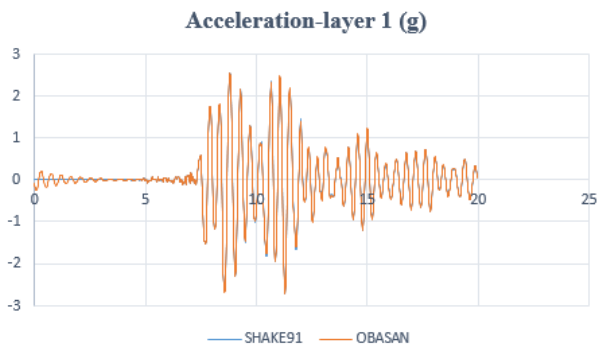


Figure 8: Kobe earthquake record motion

4.2.1. Linear response of FFGM analysis



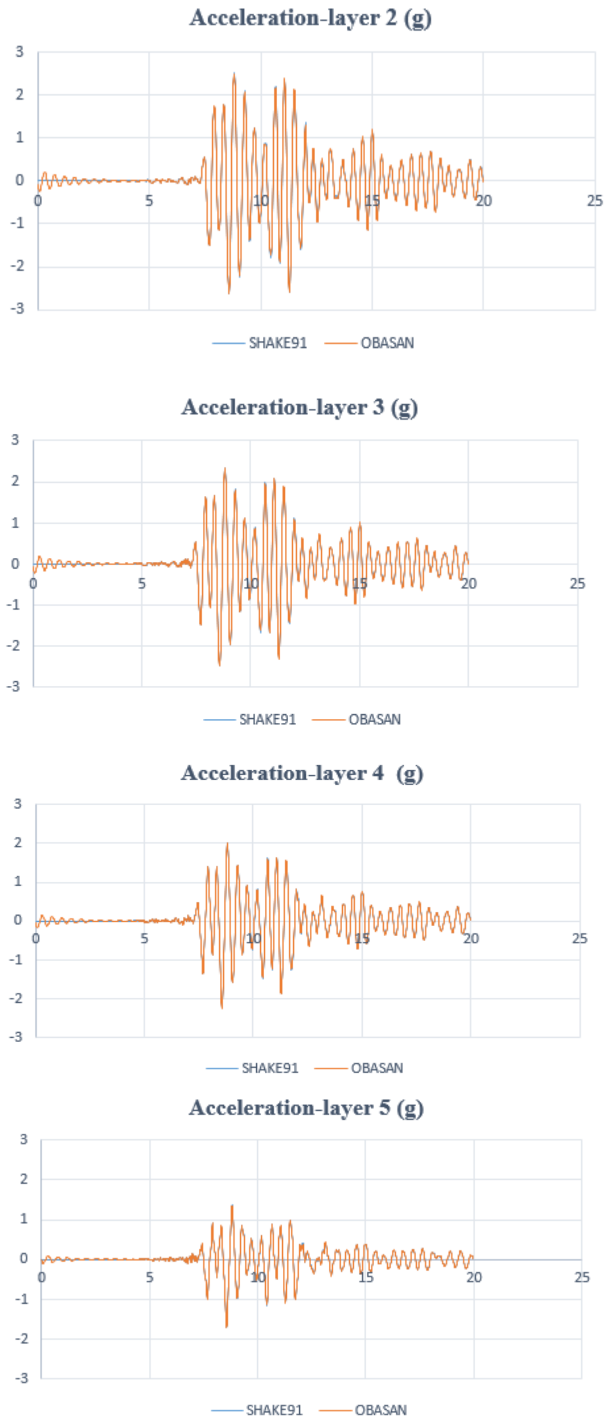
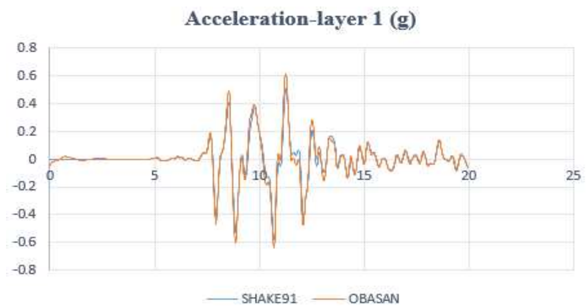


Figure 9: Linear response analysis

4.2.2. Equivalent-linear response of FFGM analysis



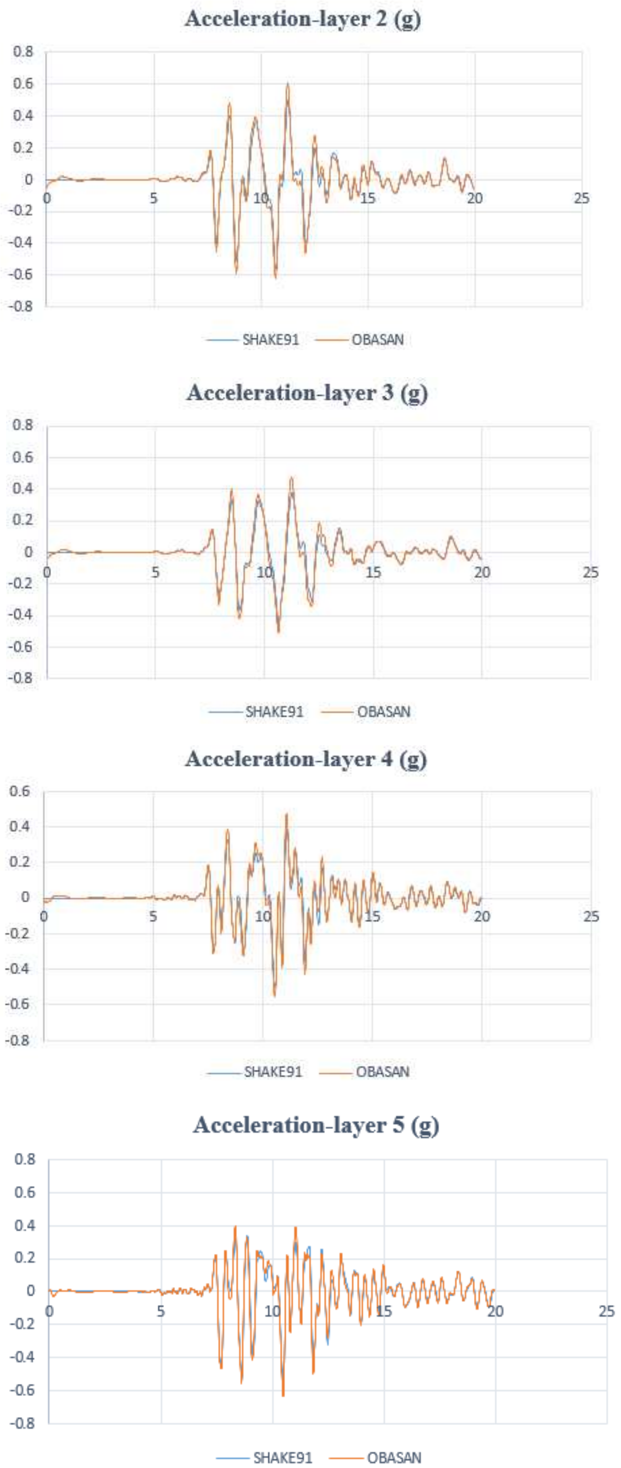


Figure 10: Equivalent-linear response analysis

According to the results above, the FFGM analysis showed a good agreement for both linear and equivalent-linear analysis between OBASAN and SHAKE91 as shown in Figures 9 and 10, respectively. This agreement confirmed that OBASAN could perform well for FFGM analysis that facilitated for SSI analysis and damaged estimation in the target city considering SSI effect.

5. ESTIMATION OF DAMAGED AREA IN THE CITY

Among many prefectures, Kochi prefecture is estimated to suffer from the great future earthquake, which will occur along Nankai Trough. Therefore, Kochi city is one of the target areas for estimating the damage.

In order to obtain the target, there are more tasks to complete such as integration of dynamic ground compliance (DGC), Geographic Information Systems (GIS) data for building information, and borehole data estimation from the existing data.

5.1 Dynamic Ground Compliance integration

Dynamic ground compliance (DGC) is a process to determine a couple of soil spring and dashpot, which is used to support and transfer ground motion to the structure. This integration facilitates determining horizontal, vertical, rocking, and torsional spring-dashpot according to different types and shapes of foundation, as shown in Figure 11. The equations of DGC are expressed in equations (6) and (7).

$$\bar{K}_i = k_i + i\omega c_i \quad (6)$$

$$\bar{K}_i = k_i\left(1 + i2\beta_i\right) \quad (7)$$

$$\beta_i = \frac{\omega c_i}{2k_i} \quad (8)$$

Where $\bar{K}_i$: complex-value function

β_i : radiation damping ratio of foundation

k_i, c_i : frequency-dependent of foundation stiffness and dashpot

Various expressions have been proposed to solve this equation according to different types of foundation and soil conditions such as the rigid surface and embedded foundation [Mylonakis et al., 2006] [Gazetas, 1983] [Gazetas, 1991] [Pais et al., 1988] and pile foundations [NIST, 2012].

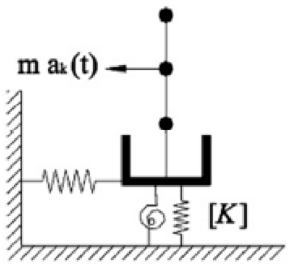


Figure 11: Spring-dashpot of foundation-soil system

5.2 GIS data for building and borehole information

In order to construct buildings in a target city, GIS data for building information is very important. These buildings' data give necessary information such as building shape, height, type (RC, steel), etc. GIS data of building information in Kochi city was shown in Figure 12 and the target area is selected for damage estimation.

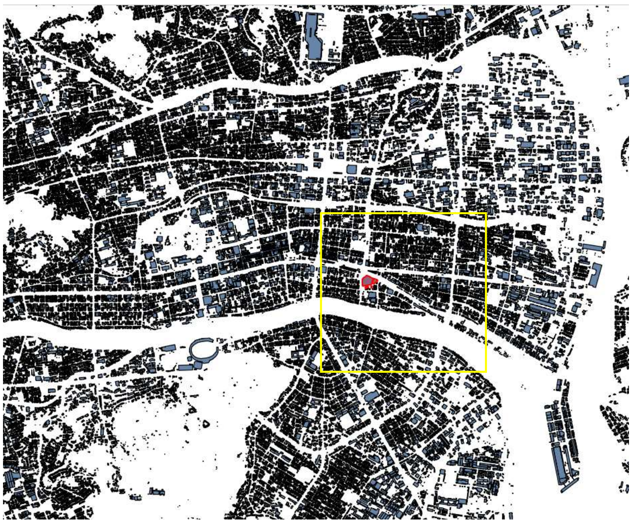


Figure 12: GIS data of buildings in Kochi city

Some information of borehole data can be obtained by GIS data. However, due to the limitation of borehole data in the city area, the estimation data is necessary and can be achieved by using the interpolation model [Yamashita et al., 2015].

5.3 Visualization and structural response

As mentioned above, OBASAN was integrated into IES. The visualization of damage area was indicated under IES as shown in Figure 13, while structural analysis was performed under OBASAN. In the target area, drift angle of each story was considered as structural damage, which can be categorized as fully operational, operational, life safe, and collapsed. According to these categories, the most damaged area in the city was clarified and the safety shelters were indicated for local residents during the mega disaster, which can occur any time and without alert in advance.

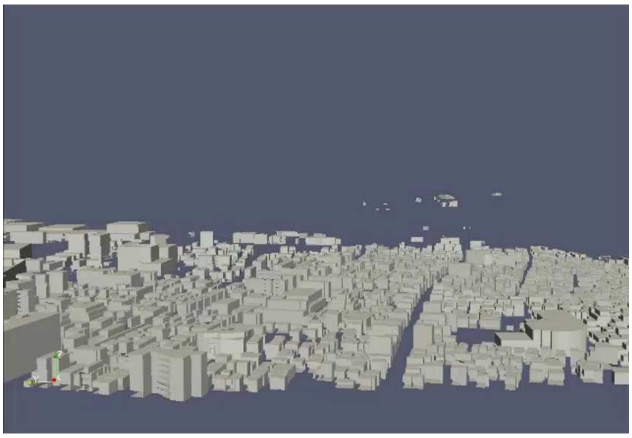


Figure13: Visualization of buildings in Kochi city, in IES

6. CONCLUSION

After the experiences of the 2011 Great East Earthquake, various prevention plans have been constructed. Among them, many advanced application tools for damaged area estimation have been invented. OBASAN is a potential tool for structural analysis and integrated into IES for simulating the damaged area estimation in the city.

However, the estimation was done only with fixed base structure, which was unable to perform an actual response of structure under soil interaction during a high intensity earthquake. Therefore, the objective of this paper is to enhance the capacity of OBASAN to perform FFGM analysis, which facilitates to determine ground motion amplification and SSI analysis.

The FFGM analysis showed a good agreement for both linear and equivalent-linear analysis between OBASAN and SHAKE91, which is a widely used program for ground motion analysis in FD. Thus, OBASAN became a potential tool for structural and FFGM analysis.

For further extension, dynamic ground compliance (DGC) integration is another important factor, which is used to determine soil spring-dashpot and transfer foundation motion to superstructure. These integrations facilitate performing the structural response under earthquake and tsunami disaster considering SSI effect.

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