PRACTICAL APPLICATIONS OF EARTHQUAKE AND TSUNAMI SIMULATION OUTPUT FOR DISASTER MANAGEMENT

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ABSTRACT**:** Earthquake and tsunami simulation is one example of advanced computer technology for predicting and visualizing structural damage of all buildings in a target area. With structural analysis results, earthquake and tsunami simulation can provide reliable output of structural damage in selected earthquake scenarios. Applying a set of such reliable output to disaster management, prevention measures can be constructed to protect human life and property in the earthquake scenarios. This paper proposes practical applications of earthquake and tsunami simulation output in disaster management point of view. In earthquake and tsunami simulation output, each individual building is considered separately as micro output, and all buildings of the target area are considered simultaneously as macro output. Based on the micro output, a strengthening plan for existing buildings and a construction guideline for new buildings can be developed from predicted structural damage of each individual building. Based on the macro output, visualization of earthquake and tsunami simulation output can classify the range of building damage and indicate a weak point of the target area in order to control overall damage and increase people's awareness. In the future, integrated earthquake and tsunami simulation with evacuation models will help for better evaluation of the present evacuation methods, routes, and shelters.

KEYWORDS: earthquake and tsunami simulation, micro and macro output, disaster management

1. INTRODUCTION

On 11th March 2011, the Great East Japan earthquake and tsunami occurred in the Tohoku region. It was the largest earthquake (M9.0) in the history of Japan which caused a wide range of devastating damages and a devastating tsunami with the maximum height of 40 m. The tsunami caused about 19,000 casualties and more than 676,000 damaged buildings [Suppasri et al., 2012]. In the future, severe damage by earthquake and tsunami may occur in the Tokai, Tonankai, and Nankai region as shown in Figure 1. Due to the awareness of disaster evacuation, people's experience with past earthquake and tsunami can reduce the fatality ratio in coastal areas [Suppasri et al., 2012]. Therefore, disaster recognition of people is very important in disaster management. For inexperienced people, visualization of earthquake and tsunami simulation output may help to increase their awareness. Based on lessons learned from past earthquake and tsunami, the reliability of damage prediction can be significantly improved and countermeasures can be constructed for disaster prevention.

In order to reduce the social and economic impact of earthquake and tsunami, computer simulations are applied to selected earthquake scenarios. In earthquake and tsunami simulation, thousands of buildings are modeled to predict structural damage in order to consider individual and overall damage in a target area. Integrated Earthquake Simulation (IES) is an earthquake simulation tool for predicting and illustrating structural damage of all buildings simultaneously [Hori et al., 2008]. For tsunami simulation, all buildings are modeled by means of the same approach as IES to determine hydrodynamic force, which may vary upon building arrangements and shapes. Object-Based Structural Analysis (OBASAN) is used to perform reliable nonlinear structural analysis of each building [Latcharote et al., 2013]. Due to earthquake ground motion and hydrodynamic force, structural damage of each building is predicted from strength capacity of structural elements. The earthquake and tsunami simulation output can provide effective prevention measures and raise awareness of disaster prevention among people in the target area.

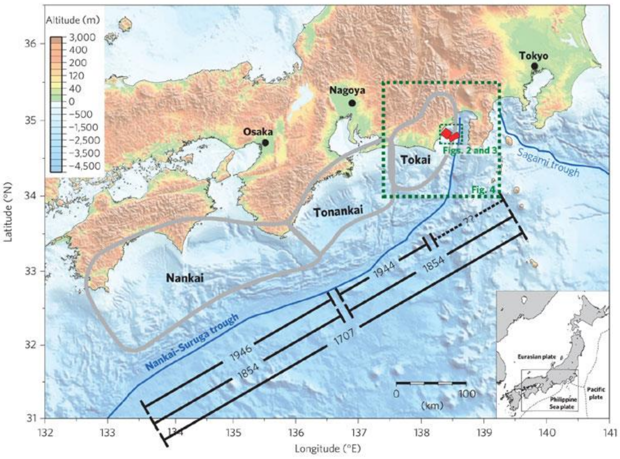

Figure 1 The seismic zone along the Nankai-Saruga Trough [Aoi et al., 2010]

2. POSSIBLE DAMAGE IN EARTHQUAKE AND TSUNAMI

For disaster management, prevention measures are very important to protect human life and property in a future earthquake and tsunami. In order to construct prevention measures, future damage should be predicted based on observed damage from past earthquake and tsunami. Therefore, reliable damage prediction has a significant effect on people living in a target area. For damage prediction, less estimated damage may lead to more loss in the future event. From past earthquake and tsunami, damaged buildings can be observed to realize their failure behavior due to earthquake ground motion and tsunami hydrodynamic force. Investigating building damage caused by earthquake and tsunami and integrating them to earthquake and tsunami simulation can provide reliable output for disaster management.

2.1 Example of observed damage by the 2011 Great East Japan earthquake and tsunami

During the 2011 Great East Japan earthquake and tsunami, many buildings were damaged by the combination of following items; earthquake ground motion, liquefaction, tsunami hydrodynamic force, and floating debris. All damaged buildings were classified into different levels of building damage, such as partial damage, partial collapse, and complete collapse. An estimated number of all damaged buildings are shown in Table 1. Where most of the damaged buildings were wooden houses. Therefore, structural analysis of wooden houses should be emphasized more in earthquake and tsunami simulation.

Table 1 Number of damaged buildings from the 2011 Great East Japan earthquake and tsunami

Type of buildings	Number of buildings	%
Reinforced concrete	5,304	2.62
Steel	10,716	5.29
Wooden	168,610	83.27
Masonry and others	17,862	8.82

Figure 2 Reinforced concrete building collapsed by the earthquake in Sendai

Figure 2 shows a reinforced concrete building collapsed by the earthquake ground motion that caused column failure at the first floor of this building. Based on a building design code, earthquake resistance design of this reinforced concrete building was not enough to prevent building collapse. Furthermore, it might occur because this is a soft-story building.

Figure 3 Overall damage from earthquake and subsequent tsunami in Onagawa

Figure 3 shows overall damage in a whole area caused by earthquake and subsequent tsunami. Some reinforced concrete buildings were overturned by liquefaction, buoyancy force, and hydrodynamic force. Some survived reinforced concrete buildings were partially damaged, and some were not damaged. In addition, some steel frame buildings were partially collapsed by earthquake ground motion and hydrodynamic force.

Figure 4 shows wooden houses collapsed by earthquake and subsequent tsunami. These collapsed wooden houses became floating debris during a tsunami. With tsunami flow, impact force caused by floating debris, including boat and car, might act on buildings and cause serious damage to the buildings.

Figure 4 Damage magnifying by the debris impact in Onagawa

Figure 5 shows building damage caused by fire in a residential area. Depending on the wind speed and direction, debris amount, and beach slope, vehicle’s battery, electricity and fuel can cause a fire in both residential and industrial area during earthquake or tsunami.

Figure 5 Building damage due to earthquake and tsunami followed by fire in Kesennuma

Figure 6 shows survived buildings during earthquake and tsunami. These buildings were temporary evacuation shelters for people living in these buildings to escape from a tsunami. In the future, it is very important to confirm that these kinds of buildings, such as hospital, school, and hotel, will be safe for evacuating people from earthquake, tsunami, and other possible second disasters as mention above.

a) Hospital building in Minamisanriku

b) School building in Arahama

c) Hotel building in Watari

Figure 6 Survived reinforced concrete buildings

2.2 Possible future damage

Based on lessons learned from the 2011 event, the loss of human life and property might occur due to unexpected damage caused by earthquake and tsunami. Therefore, it is necessary to predict possible future damage, especially for designated evacuation shelters. In an evacuation plan, most high-rise reinforced concrete buildings are a designated evacuation shelter for people living in the surrounding area. During an earthquake, earthquake ground motion causes the shelter to weaken. Sequentially, hydrodynamic force from a tsunami and debris attack may cause the shelter to collapse. The shelter can be overturned by liquefaction, buoyancy force, and hydrodynamic force. The access to roof of the shelter, such as corridor and stair, should be considered for evacuating people. With considering all possible damage in the future, earthquake and tsunami simulation can provide reliable output to construct prevention measures.

3. EARTHQUAKE AND TSUNAMI SIMULATION

The previous section illustrates buildings suffering damage from past earthquake and tsunami which should be focused in earthquake and tsunami simulation. Based on observed damage, it indicates that earthquake ground motion, hydrodynamic force, liquefaction, buoyancy force, and debris should be taken into account in structural analysis. However, this is the first attempt to integrate earthquake simulation and tsunami simulation, so only earthquake ground motion and hydrodynamic force are considered in nonlinear structural analysis of buildings, which suffer damage from earthquake and subsequent tsunami. With structural element models, each building can be represented as mass model, such as single degree of freedom (SDOF) and multi degree of freedom (MDOF) model, and structural frame model, such as beam-column and wall-frame model. These mass and structural frame model can be selected for buildings of most common types, including reinforced concrete, steel, wooden, base-isolated, and composite buildings, based on observed damage of each building type.

3.1 Building modeling

In earthquake and tsunami simulation, thousands of buildings are modeled to predict structural damage in order to consider individual and overall damage in a target area. All buildings are represented as a set of structural element models, such as beam, column, and wall, to perform nonlinear structural analysis. For each building, a structural frame can be generated from Geographic Information System (GIS) data, such as building shapes, building types, number of floors, and construction year, as shown in Figure 7. Based on a building design code, strength capacity of structural elements is estimated to predict structural damage of each building. With strength capacity of structural elements, the bending moment-curvature and shear stress-strain relationship are developed to perform nonlinear structural analysis with hysteresis models, and predict structural damage from structural analysis results.

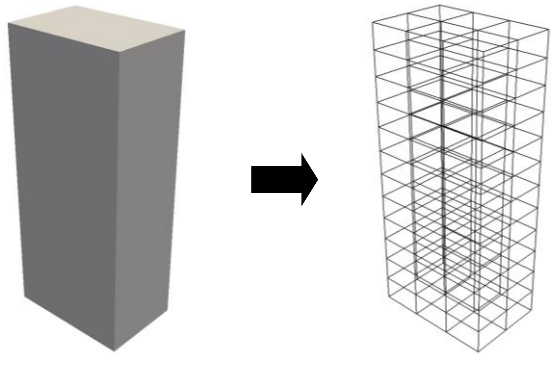

Figure 7 Common Modeling Data (CMD) [Hori et al., 2008]

3.2 Nonlinear structural analysis

In earthquake scenarios, an earthquake occurs beneath a city area and earthquake ground motion causes structural damage to all buildings. Then a tsunami reaches the city area and hydrodynamic force causes more structural damage to all buildings. With building modeling, each building is represented as a set of structural element models, which can be analyzed by inputting sequential excitation loads of earthquake and tsunami as shown in Figure 8. For structural element models, beam is a line element model for connecting two nodes in horizontal plane; column is a line element model for connecting two nodes in vertical plane; wall is a quadratic element model for connecting four nodes in vertical plane.

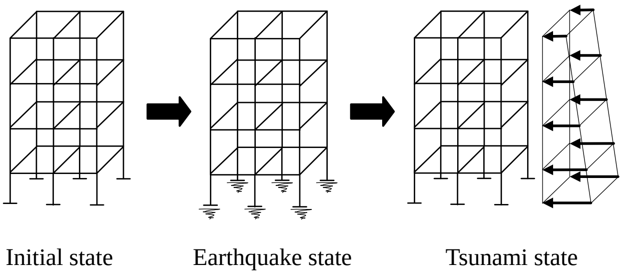

Figure 8 Sequential excitation loads

In the case of earthquake, dynamic structural response analysis is performed to predict damage of buildings, which are subject to earthquake ground motions. Sequentially, static structural analysis is performed to predict more damage to buildings, which are subject to hydrodynamic force from a tsunami. In the future, structural analysis of buildings should consider liquefaction, buoyancy force, and debris from a tsunami.

3.3 Damage prediction

Due to nonlinear structural analysis, structural damage of all buildings is predicted from structural analysis results in order to consider individual and overall damage in earthquake and tsunami simulation. For predicting structural damage, structural analysis results are classified to node, element, modal, and hysteresis output. Node output is structural analysis results of each node, such as displacement, velocity, acceleration, and reaction force; element output is structural analysis results of each structural element, such as stress, strain, deformation, and internal force (e.g., bending moment, shear force, and axial force); modal output is dynamic characteristics of buildings, such as eigenvalue, eigenvector, period, and frequency; hysteresis output is nonlinear analysis results of each structural element, such as ductility and stiffness degrading factor.

For each story of a building, story displacement is calculated from node output, and drift angle is calculated from relative story displacement and floor height. Based on a building design code, maximum drift angle can classify the level of building damage. For each structural element of a building, bending moment, deformation, stress, and strain are calculated from element output, and structural damage can be classified from the range of the bending moment-curvature and shear stress-strain relationship. With structural analysis results, earthquake and tsunami simulation can provide reliable output of structural damage in selected earthquake scenarios. Applying a set of such reliable output to disaster management, prevention measures can be constructed to protect human life and property in the earthquake scenarios.

4. MICRO AND MACRO OUTPUT

4.1 Micro output

In earthquake and tsunami simulation, thousands of buildings are modeled, and micro output is damage prediction of each individual building in a target area. For the micro output, each individual building is modeled as a structural frame, as shown in Figure 8, in order to obtain reliable prediction of structural damage. For a building, structural damage of each structural element is predicted from element output of beam, column, and wall to consider structural damage of a whole building from earthquake and subsequent tsunami. The level of building damage can be classified into elastic limit, functional limit, safety limit, and collapse.

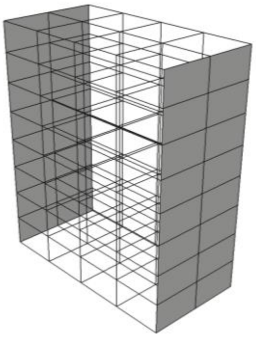

Figure 8 Individual building in earthquake and tsunami simulation

4.2 Macro output

In earthquake and tsunami simulation, macro output is damage prediction of all buildings simultaneously in a target area. For macro output, all buildings are modeled as shown in Figure 9, in order to obtain reliable prediction of overall damage in the target area. For all buildings, structural damage of each building is predicted from drift angle of each story to consider structural damage of a whole building from earthquake and subsequent tsunami. In the target area, the level of building damage can be classified into elastic limit, functional limit, safety limit, and collapse.

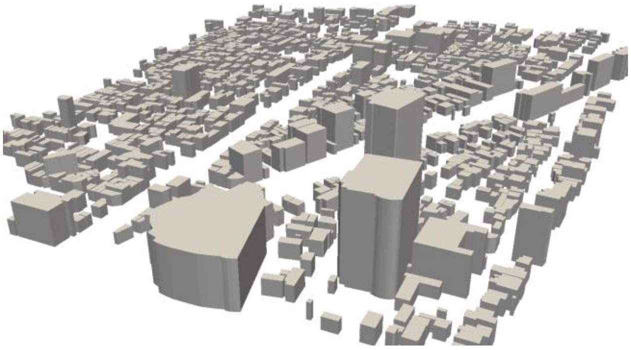

Figure 9 All buildings in earthquake and tsunami simulation

5. PREVENTION MEASURES

In a target area, micro output is applied to construct prevention measures from earthquake and subsequent tsunami. For prevention measures, some existing buildings are a designated evacuation shelter for people living in the surrounding area, so these existing buildings should be considered carefully by the micro output of earthquake and tsunami simulation. For the micro output, each individual building is modeled as a structural frame to predict structural damage of beam, column, and wall, so the micro output can be used to develop a strengthening plan for existing buildings and a construction guideline for new buildings in case of earthquake and subsequent tsunami.

In a target area, macro output is applied to select the location of a designated evacuation shelter, which depends on location of high rise buildings and number of people living in the surrounding area. Based on the macro output, visualization of earthquake and tsunami simulation output can classify the range of building damage and indicate a weak point of the target area in order to control overall damage and increase people's awareness.

6. CONCLUSION

In order to construct prevention measures, micro and macro output of earthquake and tsunami simulation are conducted to predict building damage in a future earthquake and tsunami. The earthquake and tsunami simulation output should cover all possible damage which may occur in the future, and it should be acceptable with reliable prediction for effective prevention measures. Furthermore, the visualization of earthquake and tsunami simulation output is very important to raise awareness of disaster prevention among people. In the future, integrated earthquake and tsunami simulation with evacuation models will help for better evaluation of the present evacuation methods, routes, and shelters.

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