

# 論文内容の要旨

## **Introduction**

On 11<sup>th</sup> 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. During the 2011 Great East Japan earthquake and tsunami, many buildings were seriously damaged by a combination of following items; strong ground motion, tsunami flow, debris impact, and soil liquefaction. In the future, severe damage by earthquake and tsunami may occur in the Tokai, Tonankai, and Nankai region as serious as the 2011 Great East Japan earthquake and tsunami. Therefore, prevention measures are very important to reduce damage from next great earthquake and tsunami.

## **Failure mechanism of overturned buildings in Onagawa town**

During the 2011 Great East Japan earthquake and tsunami, unless many buildings were damaged and collapsed by strong ground motion and tsunami flow, six overturned buildings were founded unexpectedly in Onagawa town. Overturning and resisting moment resulting from hydrodynamic force, buoyancy force, building self-weight, and pile resistance force were considered to investigate the mechanism of building overturning. Based on our survey data, most piles were probably broken by ground shaking and soil liquefaction, which easily caused piles to be pulled out of the ground and then fail in tension. Soil liquefaction changed soil properties and caused loss of friction between soil and piles due to the loosening of soil around the piles. Based on previous research on geotechnical problems, a practical method was suggested to evaluate soil-pile friction when soil liquefaction occurred. From analysis results of these overturned buildings, it was found that a pile foundation was more effective than a shallow foundation, but joint failure between piles and pile caps resulting from ground

shaking in earthquake must be considered in pile design. In addition, loss of friction between piles and soil due to soil liquefaction must be taken into consideration in soil analysis and pile design. The results indicate that soil liquefaction has as significant an effect on building overturning as buoyancy force, which depends on opening ratio of buildings. The results obtained here demonstrated that pile resistance capacity and building self-weight must be sufficient to resist overturning failure of buildings. Applications of these findings would greatly improve building design guidelines aimed to protect overturning failure of buildings, especially for tsunami evacuation buildings, which must be maximally secured for disaster evacuation.

### **Development of macro plate model for reinforced concrete walls**

This research focuses on structural damage of reinforced concrete buildings from earthquake and subsequent tsunami. In RC buildings, reinforced concrete walls are widely used to increase resistance against lateral loads imposed by wind, earthquake, and tsunami. Many analytical models have been proposed for nonlinear analysis of shear walls which are classified as microscopic and macroscopic models, representing local and overall behavior of RC walls respectively. This research proposes macro plate model, a macroscopic model representing a wall member in RC walls. The entire wall member was modeled as a rectangular plane member assuming uniform concrete plate and uniformly orthogonal bar arrangement in order to consider in-plane and out-of-plane behavior. Macro plate model was a four-node element model which was developed originally from the theory of elasticity proposed by Timoshenko for in-plane behavior using the plane-sections-remain-plane assumption and the theory of plate bending proposed by Zienkiewicz for out-of-plane behavior using out-of-plane shape function. For out-of-plane deformation, out-of-plane pure bending deformation was incorporated with out-of-plane shear deformation in order to obtain more realistic behavior, in which out-of-plane behavior of a wall member should be more softening. For macro plate, hysteretic behavior can be expressed directly in member level in order to predict inelastic response of the entire RC wall. Since macro plate was developed from elastic response of plate element, numerical derivations of stress and strain in macro plate was formulated to consider inelastic response of RC walls using hysteretic stress-strain relationships in simplified hysteretic rules, such as origin-oriented

hysteresis model and axial-stiffness hysteresis model, and other hysteretic models from experimental results in order to track nonlinear responses. Due to a four-node element model, the solution of wind and tsunami problem was proposed to convert from distributed force to nodal force acting on each node of macro plate model.

Implementation of macro plate model, a practical model, into a computational platform will provide structural design engineers and researchers improved analytical capabilities to model and study the behavior of RC walls and their interaction with other structural members. The practical model can be used for nonlinear structural analysis of RC buildings represented by a wall-frame model. The reliability of a wall-frame model depends on hysteresis models of structural members and member interaction. This practical model allows for possible further model improvements including applications to other structural members and joints.

### **Extension of nonlinear structural analysis from earthquake response to tsunami response**

The main objective in a research field of earthquake engineering is to reduce the loss of human life during earthquake and tsunami. Based on this objective, it is very important to prevent building collapse from earthquake and subsequent tsunami. For reinforced concrete wall-frame buildings, experimental and analytical studies have been carried out to understand building collapse from earthquake. Nonlinear structural analysis of RC wall-frame buildings focusing on earthquake response has been proposed in many previous research studies. In this research, analytical studies were carried out to propose nonlinear structural analysis of RC wall-frame buildings subjected to earthquake and subsequent tsunami. For a nonlinear analytical model of RC wall-frame buildings, a macro frame model was used to represent a beam and column member and a macro plate model was used to represent a wall member. In order to consider out-of-plane strength of wall especially in the case of tsunami, the macro plate model was proposed to simulate out-of-plane behavior of shear and bending. For simulating sequential behavior of earthquake and tsunami response, a nonlinear analytical model of the six-story RC wall-frame building was carried out to perform nonlinear structural analysis by means of the same hysteresis models.

### **Verification with a six-story reinforced concrete wall-frame building**

For the case of earthquake, a proposed nonlinear analytical model, in which, hysteretic behavior of beam, column, and wall is simulated to predict inelastic response on member level, was verified with a six-story RC wall-frame building tested at E-Defense. Three ground motion components in the east-west, north-south, and up-down direction of Kobe earthquake recorded by Japan Meteorological Agency (JMA 1995) were an input ground motion as same as the test at E-Defense. Since the one-component model and the proposed macro plate model are still not capable of simulating strength degradation in post-peak response, only stiffness degradation was considered in the nonlinear analytical model. The input ground motion was scaled by 25% and 50% and applied to the proposed nonlinear analytical model. From the results of dynamic structural response analysis, the relationship between base shear and relative displacement at 2<sup>nd</sup> floor was considered for verification. Based on the verification results of this nonlinear analytical model with the test at E-Defense, The results show a good correlation for 25% and 50% of input ground motion without considering post-peak response, although the input data of ground motion was slightly different from the test at E-Defense.

### **Verification with a three-story reinforced concrete wall-frame building**

For the case of tsunami, this analytical model was verified with a three-story RC wall-frame building damaged by only tsunami in the 2011 Great East Japan earthquake and tsunami. The out-of-plane deformation was occurred in outer frame of this three-story building by tsunami load. The outer frame consisted of column, transverse beam, and transverse wall. The damaged transverse wall covered two-story and four-span section without floor slabs on second and third floor. For this analytical model, hydrostatic pressure was assumed to be input tsunami load as fully distributed load in triangular shape. Input tsunami load was assigned to the outer frame of this analytical model in which hydrostatic pressure was varied by tsunami inundation depth from 0.0 m to 10.5 m. The proposed macro plate model was used to represent transverse wall in order to investigate out-of-plane behavior. Varying with tsunami inundation depth, bending moment and shear force were considered for the failure behavior of transverse beam and column: out-of-plane bending moment and shear force were

considered for the failure behavior of transverse wall. Since the reinforcement ratio of transverse wall was small, out-of-plane yield strength was less than out-of-plane crack strength. In order to compare the analysis results with observed damage, two analysis cases were investigated in this study. For CASE-I, out-of-plane crack strength was considered as a failure point, so that transverse wall was assumed to be failed after this point. For CASE-II, strength degradation was considered for out-of-plane strength, so that out-of-plane force was decreased after the cracking point. The static push-over analysis was performed by varying tsunami inundation depth from 0.0 m to 10.5 m to obtain the results of CASE-I and CASE-II. Based on the verification results of this analytical model with observed damage from tsunami in the 2011 Great East Japan earthquake and tsunami, the results of CASE-I, in which strength degradation was ignored in out-of-plane strength of transverse wall, seem to comply with observed damage. For CASE-II in which strength degradation was considered in out-of-plane strength of that, the results seem not to comply with observed damage. However, tsunami load in real situation might be larger than the calculated hydrostatic pressure. Comparing the analysis results between CASE-I without strength degradation and CASE-II with strength degradation, it was found that the proposed macro plate model can simulate well out-of plane behavior of transverse wall. However, the macro plate model must be improved to simulate strength degradation in post-peak behavior of earthquake response.

### **Sequential analysis of a six-story RC wall-frame building from earthquake and tsunami**

In order to study on nonlinear structural analysis of a reinforced concrete building suffering damage from earthquake and subsequent tsunami, a nonlinear analytical model of the six-story RC wall-frame building was carried out to investigate structural damage of beam, column, and wall. In analysis, an earthquake and tsunami scenario was simulated to occur with this six-story RC wall-frame building. In the case of earthquake, dynamic structural response analysis was performed to investigate structural damage of this building subject to strong ground motion. Sequentially, static pushover analysis was performed to investigate more structural damage to this building subject to hydrodynamic force from tsunami. For simulating sequential behavior of earthquake and tsunami response, nonlinear structural analysis was performed by

means of the same hysteresis models. For input ground motion, Kobe earthquake with scale factor 50% was applied to the nonlinear analytical model in order to perform dynamic structural response analysis from earthquake. For input tsunami load, hydrodynamic force was estimated from tsunami inundation depth and flow velocity which was divided to striking wave and receding wave. Therefore, the nonlinear analytical model was proposed to investigate structural damage of the six-story RC wall-frame building subject to a series of earthquake, striking wave, and receding wave of tsunami. From analysis results, it was found that more serious damage from sequential tsunami response was able to occur with beam, column, and wall. However, there was no more structural damage occurred from sequential tsunami response in some structural components. In some cases, increased level of structural damage after tsunami response also depended on previous level of structural damage after earthquake response, in which mode shape and mass participation in dynamic analysis have a significant effect on structural damage of each floor. From observation in analysis results, some structural components were still in linear range after earthquake and tsunami response: some structural components were in linear range during earthquake response and then cracked from tsunami response: some structural components were cracked from earthquake response and then yielding from tsunami response: some structural components were yielding from earthquake response and then more yielding from tsunami response. This study suggests that it is necessary to consider the failure mechanism of sequential behavior in order to protect reinforced concrete wall-frame buildings from earthquake and subsequent tsunami.

#### **Damage prediction of RC buildings in a whole city area from earthquake and subsequent tsunami**

Based on past experience in the Great East Japan earthquake and tsunami, many buildings were seriously damaged by earthquake and subsequent tsunami. For damage prediction in a city area, computer technology has been applied to simulate earthquake scenarios, such as Integrated Earthquake Simulation (IES). In IES, structural analysis of all buildings in a city area is performed to predict structural damage and then illustrate structural damage of all buildings simultaneously for selected earthquake scenarios. In this research, damage prediction of all reinforced concrete buildings in a

city area from earthquake and subsequent tsunami was proposed by means of the application in IES. Since IES can simulate only earthquake scenarios, IES was modified to input tsunami load acting on each building in order to simulate tsunami scenarios. For tsunami scenarios, tsunami inundation simulation was performed to obtain tsunami inundation height and velocity at each location of buildings and then estimate tsunami load which actually can vary upon building arrangement and shape. For a city area, all buildings were represented as a structural model, consisting of beam, column and wall to perform nonlinear structural analysis of each building subject to earthquake and subsequent tsunami. Then, structural damage of each building was predicted from the results of nonlinear structural analysis. Therefore, there were two main parts for the simulation of earthquake and tsunami scenarios: the first part is IES for building modelling and the second part is nonlinear structural analysis. Object-Based Structural Analysis (OBASAN), a structural analysis program, which has been developed by our laboratory, was proposed to perform nonlinear structural analysis as the second part of the simulation. For earthquake and tsunami scenarios, strong ground motion shakes all buildings and causes some structural damage to all buildings in a city area. Subsequently, a tsunami reaches the city area and tsunami load causes more structural damage to buildings. In OBASAN, all buildings were analyzed by inputting a sequential load of earthquake and tsunami. In the case of earthquake, dynamic structural response analysis was performed to predict structural damage of each building, which are subject to strong ground motion. Sequentially, static pushover analysis was performed to predict more structural damage to each buildings, which are subject to tsunami load. Since high performance computing (HPC) is a key role to carry out a sophisticated nonlinear analytical model and a large number of buildings in a city area, OpenMPI application has been applied to IES in order to enable parallel processing on the Central Processing Units (CPUs) for building modelling of all buildings. In this research, a double-layer platform of HPC was proposed to simulate earthquake and tsunami scenarios in a reasonably short time. Since OBASAN has been developed by C++ programming language, CUDA application was applied to OBASAN in order to enable parallel processing on the Graphic Processing Units (GPUs) for nonlinear structural analysis of a building. Therefore, HPC was achieved by a double layer of parallel processing on CPUs and GPUs. For the simulation of earthquake and tsunami scenarios, OpenMPI and CUDA application were able to perform parallel processing simultaneously in supercomputer.