Paper:

# Prediction of Strong Ground Motion and Building Damage in Urban Areas and Development of a Disaster Mitigation Strategy

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**Considering the increased population and functionality of urban areas, we have studied the prediction of damages to and disaster mitigation strategies for urban areas which may be devastated when large disaster strikes. We have developed high-precision, high-resolution subsurface soil structure models in Chukyo Area including Nagoya city, by which strong ground motions are first predicted for every site of the area using a pseudo-empirical Green's function method. Next, major damages are predicted based on earthquake response analyses of various structures such as energy facilities in reclaimed areas, industrial plants in alluvial plains, and high-rise buildings and ordinary school buildings in urban areas. We then have attempted to quantify disaster response capabilities of urban areas to set the target level for disaster mitigation countermeasures. Moreover, we have explained newly developed simulation tools for guiding individual residents to take disaster mitigation precautions by themselves.**

**Keywords:** strong ground motion prediction, building response, damage prediction, disaster mitigation strategy, urban area, simulation tool

## 1. Introduction

It is presumed that a massive earthquake is likely to occur along the Nankai Trough in the first half of this century. The massive earthquake, if one occurs, will affect not only Japan and Western Japan damaged area in particular but also other areas in the world. It is an obligation for Japanese people to avoid predicted disasters and hand down safe and secure societies to subsequent generations. For this purpose, all of the researchers and engineers who concern earthquake disaster mitigation should concentrate their efforts on taking effective measures. Considering highly concentrated functionality and large populations in large cities in Japan, we have studied predictions of damages to and disaster mitigation strategies for urban areas which may be devastated when disaster strikes.

First of all, we predicted strong ground motions in the reclaimed areas, alluvial plains, diluvial plateaus, and diluvial hills in the Chukyo Area, using a new method called a "pseudo-empirical Green's function method." This was done after establishing high-precision, high-resolution subsurface soil structure models in the area and especially taking care of the important soil conditions such as liquefaction in reclaimed lands, nonlinear ground response in alluvial plains, long-duration ground motion in diluvial plateaus, and effect of subsurface irregularity caused by cut-and-fill earthworks in diluvial hilly areas.

Next, we analyzed the earthquake response of structures of major facilities in urban areas to predict damages to them. We focused on large-scale power stations, factories and industrial facilities, high-rise buildings, and school buildings. The thermal power station is an important part of the infrastructure of the urban area, and factories are important bases for industries. High-rise buildings are used for offices and residents by many peoples, and schools are important for protecting children and having a special function as evacuation facility during disasters. Damages to buildings of the first three facility categories are predicted based on structural design models and observed/simulated earthquake ground inputs. For school buildings, the response properties are analyzed using newly developed models for proper prediction of realistic response and damage. This is because their designed earthquake resistant performance is much different from that which has been predicted based on experiences of actual damage survey.

Moreover, we attempted to quantify the potential for the occurrence and amount of disasters in past and modern societies in order to show clearly the vulnerability of modern societies against disasters. The quantified items include the population hit by earthquakes as classified by ground and floor vibration intensity, the number of pieces of furniture in a room, and the density of house congestion in urban area. Change of such indices in the recent

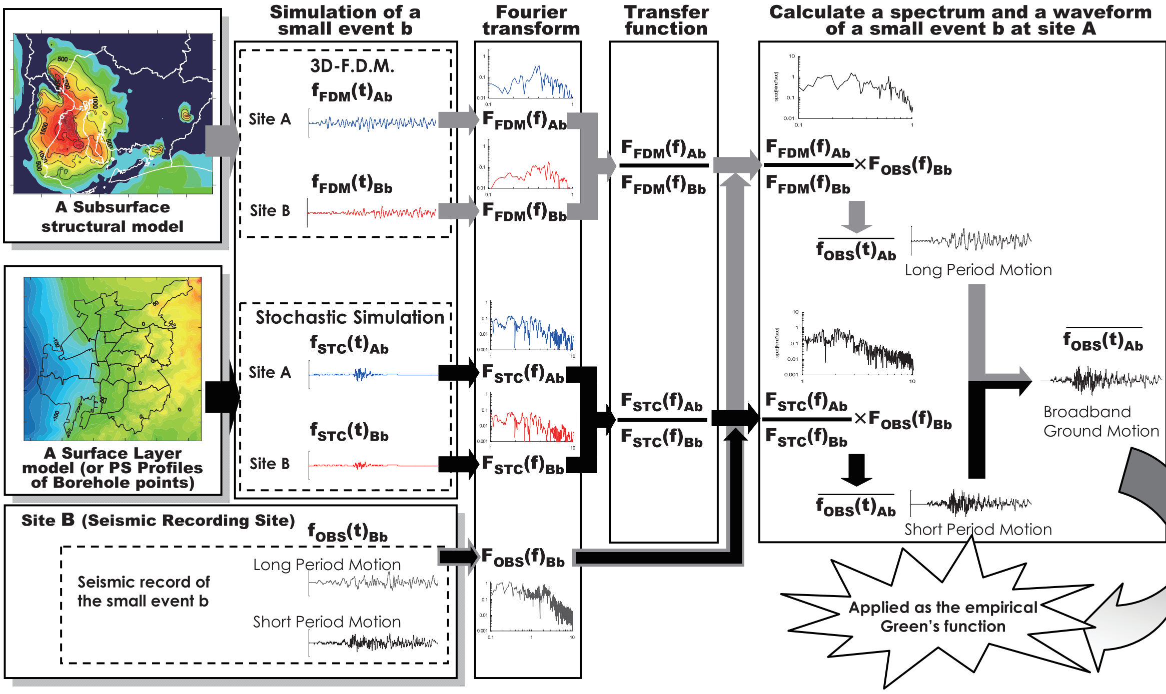
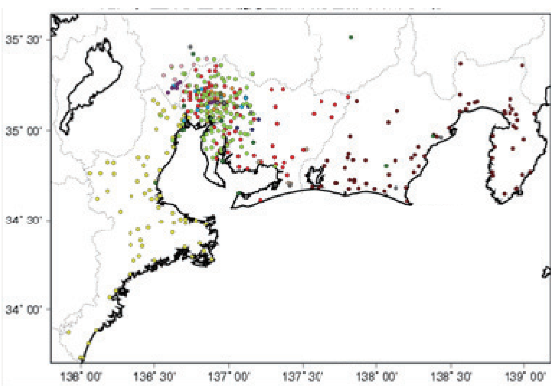



**Fig. 1.** Basic concept of pseudo empirical Green's function method to predict strong ground motion.



| Number of observation sites | |
|---|---|
| Aichi prefecture | 74 |
| Mie prefecture | 68 |
| Shizuoka prefecture | 78 |
| Nagoya city | 18 |
| Toyota city | 5 |
| Chubu electric power company | 46 |
| Toho gas company | 113 |
| Nagoya expressway public corporation | 18 |
| Oyo corporation | 4 |
| Aichi institute of technology | 119 |
| Toyohashi University of Technology | 6 |
| Nagoya university | 97 |
| K-net & KiK-net | 164 |
| Total | 810 |

(Jan/2008)

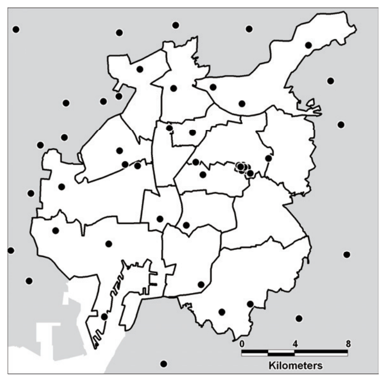



**Fig. 2.** Seismic observation sites in Tokai area (left) and Nagoya city area (right).

60 years, which means the last Tonankai earthquake hit the Chukyo area in 1944, is very important for evaluation of social vulnerability in modern cities. Furthermore, we quantified disaster response capabilities of modern society, such as firefighting, emergency rescue, medical and reconstruction capabilities. The results are used to clarify the magnitude of disasters which exceed society's response capabilities, and thereby to clarify the regional disaster mitigation targets.

Finally, based on the analyzed results, we have investigated methodologies for guiding individual residents to take suitable disaster mitigation precautions by themselves, in order to show effective aspects of disaster mitigation strategies.

This paper describes research plans executed as part of the MEXT project "Evaluation and disaster prevention research for the coming Tokai, Tonankai, and Nankai earthquakes."

## 2. Prediction of Strong Ground Motions Caused by a Massive Earthquake Occurring Along the Nankai Trough

We predicted strong ground motions in the Chukyo Area, one of the three major urban areas in Japan, based on the assumption that the Tokai and Tonankai earthquakes have occurred simultaneously along south-west coast of Japan. A pseudo-empirical Green's function method (Takahashi et al., 2008 [1]) is proposed as a strong ground motion prediction procedure which can utilize, to a maximum extent, the observed seismic records and accumulated subsurface soil structure data in the area.

**Figure 1** illustrates the basic concept of the pseudo-empirical Green's function method. At first, a transfer function is theoretically calculated between a seismic recording site (Site A) and a site at where strong ground motions will be predicted (Site B). Ground mo-

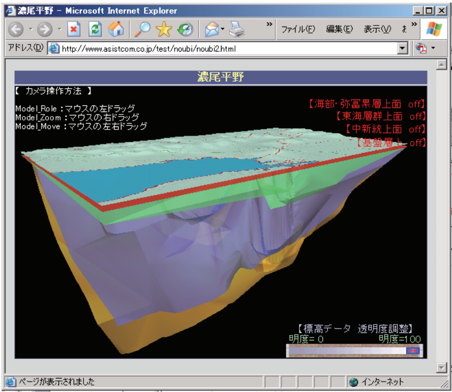



**Fig. 3.** 3-D view of deep subsurface soil structure in Nobi-plain.

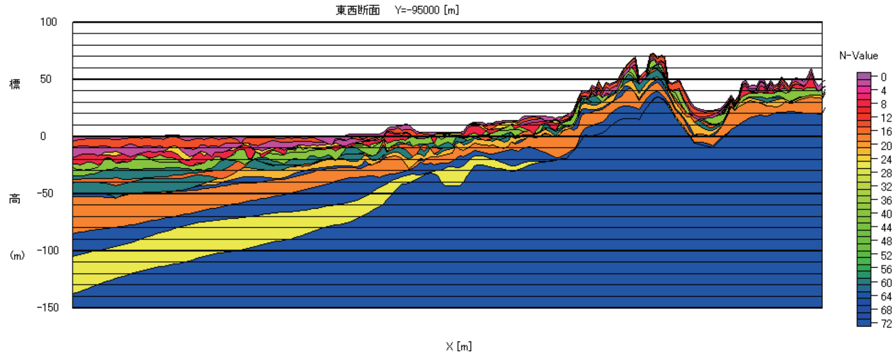



**Fig. 4.** Cross section of shallow subsurface soil structure in Nagoya-city.

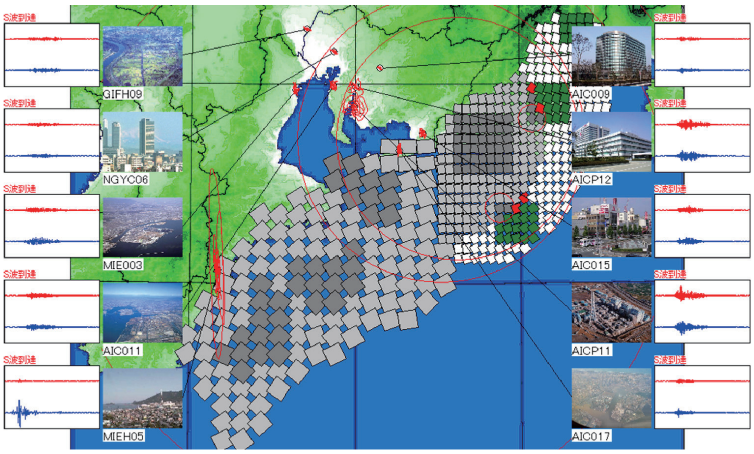



**Fig. 5.** Predicted strong ground motion in Tokai area.

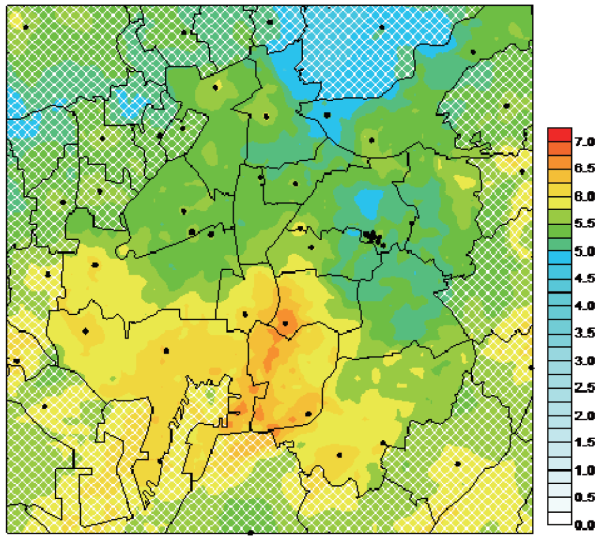


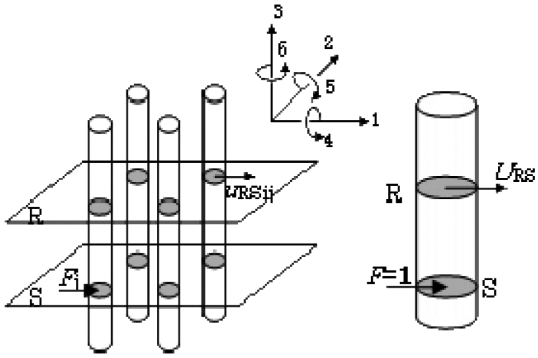

**Fig. 6.** Predicted seismic intensity (JMA) in Nagoya city area.

tions at these sites are theoretically predicted considering a point source mechanism of a small earthquake and use a hybrid procedure in which the three-dimensional finite difference method (Graves, 1996 [2]) and the statistical Green's function method (Boore, 1983 [3]) are used. Then, ground motions at Site B are given by multiplying the observed records at Site A during earthquakes by the transfer function. Finally the predicted ground motions at Site B for small earthquakes are used for synthesizing the strong motion waveforms for the large earthquakes, e.g. Tokai and Tonankai Earthquakes, at Site B by the empirical Green's function method (Irikura, 1986 [4]).

The seismic records of small- to intermediate-size earthquakes are taken from a network system (Tobita et al., 2005 [5]) to comprehensively observe strong ground motions in large urban areas. **Fig. 2** illustrates a total of more than 600 observation sites at local governments, public organizations, universities, and so forth in Aichi, Mie, Shizuoka and Gifu Prefectures, which are included in the Chukyo Area. The observation sites total about 800 when those in K-NET/KiK-net system are included. Many observation sites are located especially in and around Nagoya city as shown in the right figure. The network system provides a large number of data on small- to intermediate-sized earthquakes occurring in the Nankai Trough epicentral area.

Deep subsurface soil structures in the Nobi Plain, where the dense populated part of Chukyo Area is located, have been extensively determined by various exploratory methods, e.g., reflection, refraction, microtremor array, and gravity, in addition to investigations at deep wells. These data are compiled to produce deep subsurface soil structure models. One example is illustrated in **Fig. 3** (Aichi Prefecture, 2005 [6], and Tobita et al., 2005 [5]). Moreover, shallow subsurface structure models with a plain resolution of 50m have been established for the city of Nagoya, based on the data collected by the standard penetration tests carried out at about 40,000 wells and by PS logging tests carried out at about 340 wells. One example is illustrated in **Fig. 4** (Takahashi et al., 2006 [7]). These models include change of surface geology resulting from cut-and-fill earthworks.

**Figure 5** illustrates the predicted waveforms for Tokai and Tonankai earthquakes at the representative sites in the Tokai area together with asperity distributions of the fault **Fig. 6** illustrates the predicted seismic intensities in the




(a) Pile group (multipoint excitation)

(b) Intensive pile

**Fig. 7.** Multipoint excitation solution to model intensive pile.

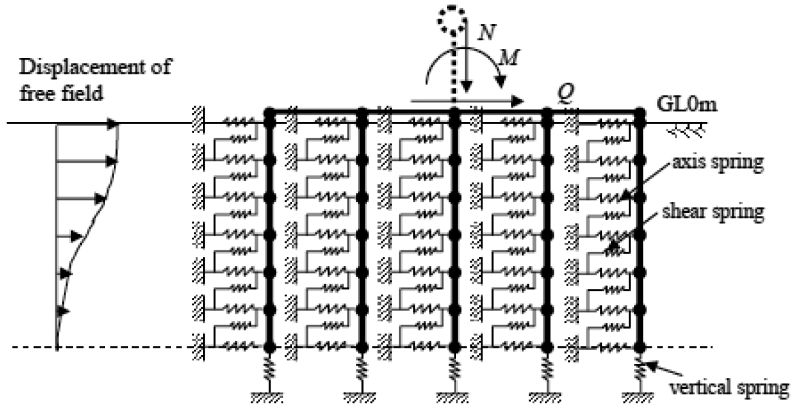



**Fig. 8.** An example of a frame model for a dynamic or static response analysis of a pile foundation.

Nagoya area by the pseudo-empirical Green's function method. It should be noted, however, that nonlinearity of the surface ground is not taken into consideration in these analyses. We are planning to predict strong ground motions in the reclaimed areas, alluvial plains, diluvial plateaus, and diluvial hills while taking into consideration nonlinearity, liquefaction, and irregularity of the surface and subsurface soil structure.

## 3. Earthquake Response Analyses of Representative Buildings

We have analyzed how structures that are representative of those which provide urban functions will respond to earthquakes in order to get a picture of damages to urban areas hit by massive earthquakes. We selected four types of buildings: (1) large scale energy facilities located on reclaimed lands in coastal areas, e.g., thermal power stations, to represent the energy providing infrastructure, (2) industrial plants located in alluvial plains where large areas are available, to represent facilities that support industry, (3) tall buildings in the central urban areas where offices and commercial facilities are concentrated, and (4) schools, which provide evacuation functions in every part of the city area.

As energy facilities are built on soft soil supported by piles, it is essential to analyze nonlinear dynamic interactions between the buildings and the soil while taking into consideration the effects of liquefaction and nonlinearity of the soil, as well as the effects of the piles. For this analysis, we adopted the dynamic substructure method, in which the thin layered element method and flexible volume method are used, and we also used another method in which a pile group is considered as an intensive pile (Fukuwa et al., 2007 [8]). **Fig. 7** illustrates the basic concept of the method, characterized by evaluation of the intensive pile, which serves as a spring representing the soil resistance. As illustrated, the spring effect by the intensive pile was analyzed by finding an average displacement of the pile group cross-sections at a vibration-receiving depth when the piles are simultaneously excited at a vibration depth. Moreover, nonlinearity of the soil was considered for the pile-supporting structures as illustrated in **Fig. 8** (Mori, et al., 2007 [9]). The objects analyzed were turbine plants, representing major buildings for thermal power station, and chimneys, representing long-period structures.

We also carried out earthquake response analyses on industrial plants located in alluvial plains while taking into consideration their construction ages and their characteristics as large steel frame structures, in addition to the soil nonlinearity and pile effect.

For tall buildings in urban areas, we developed earthquake response models based on the relation between natural period/damping and building height, which is established by the microtremor and earthquake observation records during the construction (**Fig. 9** illustrates one example, Fukawa et al., 2008 [10]) and the results of experiments with the real-size shaking table test (E-Defense illustrated in **Fig. 10**, Nagae et al., 2009 [11]), to investigate structure and indoor safety under the severe earthquake shaking caused by long-period ground motion in the sedimentary basins.

For schools, we carried out the earthquake response analyses on the typical three- or four-story reinforced concrete school buildings using the ground motions predicted at various sites in the city of Nagoya to predict the damages. Expected damages of buildings before and after earthquake retrofitting were also investigated. The analysis model used for the prediction is based on the model which can explain school building damages observed in the 1995 Kobe Earthquake (Shirase et al., 2006 [12]), where the revised model includes the effects of soil nonlinearity and geometrical nonlinearity caused by foundation uplift, sliding, and so forth.

## 4. Vulnerability and Disaster Response Capabilities of the Modern Societies

The ground motion of the same amplitude can cause different amounts of damage, depending on differences in

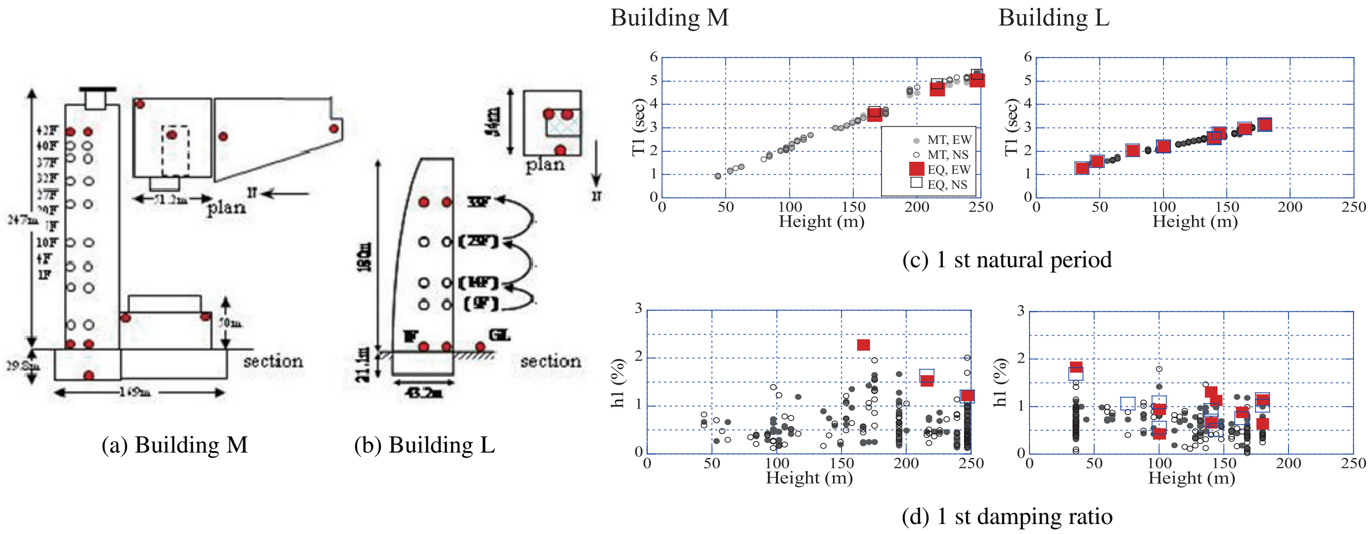



**Fig. 9.** Natural period and damping of tall buildings obtained from earthquake response and ambient vibration during construction.

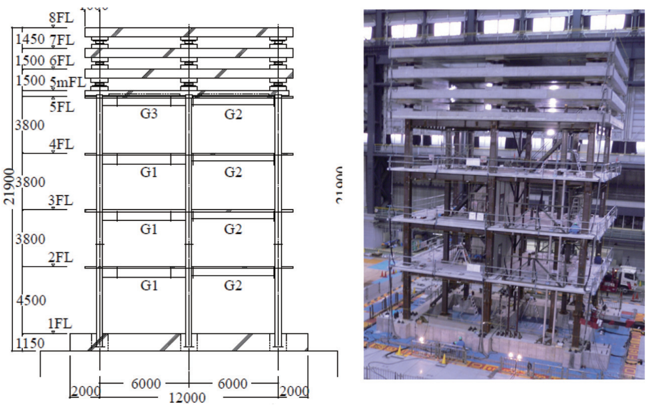



**Fig. 10.** Outline of E-Defense experiment of tall building.

the vulnerability of urban areas and communities. Large earthquakes have occurred repeatedly along the Nankai Trough in approximately every one hundred years, but societies and communities have changed greatly with time. We analyzed the temporal transition of communities' vulnerability and the disaster response capabilities of modern society.

Japan's population has almost tripled in the past 100 years, and the increased population has been concentrated in urban areas. As a result, urban areas have expanded to soft soil while buildings have become taller and more closely spaced. Houses have come to have more furniture as society has become more affluent. Urban areas that have expanded widely have raised railroads/roads and subways for high-speed transportation, and the number of elevators has also increased. These areas have also increased the number of energy facilities and industrial plants to sustain the affluence, concentrating these facilities on soft soil and reclaimed land in coastal areas, and have also expanded power, gas, water, sewage, and communication and information networks. These lifelines, although they make society convenient, increase the magnitude of adverse effects when they are disrupted.

Buildings on soft soil and upper floors generally shake more during earthquakes. The increase in population has significantly increased the number of people living in vulnerable areas. At the same time, the number of indoor victims will increase because of the increase in pieces of furniture. Congested houses and an increased number of indoor victims will aggravate fire hazards. Expanded urban areas will increase the number of people who cannot return home in the event of earthquakes, and building verticalization will increase the number of people who become trapped in buildings.

Therefore, we analyzed temporal transitions that could affect the population: the number of pieces of furniture, house congestion, and building plot ratio, by classifying the population by magnitude of ground motions and by the degree to which room in the houses are shaken, in order to quantify increased vulnerability.

Next, we attempted to quantify response capabilities of firefighting, medical, and construction systems, as these are essential to the rescue and reconstruction processes, in order to quantify the disaster response capabilities of the societies and thereby to identify bottlenecks during reconstruction periods. Moreover, we have analyzed regional differences in current disaster response capabilities. This was in order to clarify seismic retrofit targets with a view to designating them as regional mitigation targets, based on disaster levels with which the societies in those regional areas can cope.

## 5. Development of a Simulator Tool for Informing the General Public of Analysis Results

We developed a new simulation tool for informing the general public of the results obtained in this study. We developed a kind of web-based geographic information system (WebGIS) to predict the relation between the magnitude of house shaking and collapse risk to guide them in taking disaster-prevention measures (Tobita et al., 2008). This system adopts GIS capable of simultaneously displaying two images to predict liquefaction risk for individual regions or compare predicted aerial views with the current ones, helping them to visualize and understand the magnitude of hazards by means of viewing the changes to landforms. The results obtained in the analysis done in this study are built into the system to add its function of predicting soil velocity structures at an arbitrary site in Nagoya, strong ground motions, and earthquake responses based on the predicted motions when the number of floors, building size, and structural characteristics are input. The shaking of the soil and response of the floor predicted by the newly developed system are updated by the experiments with small and large biaxial shaking tables (Fukawa, et al., 2008 [14]).

The residents can understand earthquake conditions beforehand and are expected to take specific disaster-preventing actions in the event of earthquakes.

## 6. Conclusion

This study intends to show the realistic situation of earthquake damage of modern city and society, and to clarify the most effective and reasonable measure against them. For the purpose, strong ground motion is predicted with high-resolution images that correspond to earthquake scenarios for Tokai and Tonankai earthquakes in specific urban areas. It precisely predicts the earthquake response of individual structures and damages to them, based on their predicted dynamic properties. This study also investigates the disaster response capabilities of individual regions as viewed by architects, clarifies problems associated with reconstruction of societies and urban areas, establishes a system for informing the general public of the results of the analysis in an easily understandable manner, and investigates a method of guiding them to take specific disaster mitigation precautions.

As a first report of this study, this paper outlines a method of precisely evaluating, based on earthquake observation records and response analysis results, strong and long period ground motions that may prevail in large sedimentary basins. It also outlines a method for evaluating the responses of long-period structures, e.g., very tall buildings, and important energy facilities located in reclaimed areas. It proposes a method for precisely predicting damages to reinforced concrete buildings, e.g., schools and collective housing buildings. Finally, it outlines a method of investigating the disaster response capabilities of individual regional communities from the viewpoint of architects and presenting some of the analysis results obtained so far.

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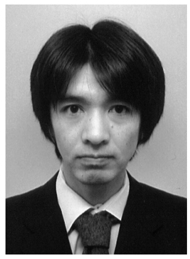

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