



## **INTEGRATED EARTHQUAKE DISASTER SIMULATION SYSTEMS FOR THE HIGHLY-NETWORKED INFORMATION SOCIETY**

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### **SUMMARY**

In 2002 the Ministry of Education, Culture, Sports, Science and Technology of the Japanese Government started assigned project to mobilize leading-edge information technologies to develop the second generation information system for earthquake disaster simulation and mitigation management, which is called as the Integrated Earthquake Disaster Simulation Systems. The realized simulation system is an integration of computer science, database technology and earthquake engineering. It is developed to be low cost and highly functional, and has features to seamlessly comprise daily operations and disaster relief operations in a municipal government. Key components of the system are the large-scale distributed simulation, the risk-adaptive regional management information technology using the Spatial-Temporal GIS, the multi-agent model simulators for emergency and recovery actions, and the damage and disaster progression simulators concerning urban residents and structures. This system shares its database with daily management system to avoid the annoying database maintenance and utilizes the PC of daily operations to achieve low cost and user-friendliness at the same time. The authors are involving in this development, which will continue until 2007. This paper presents the realized system and the prospective goal in detail.

### **INTRODUCTION**

The Great Kobe Earthquake in 1995 caused devastating damage in the highly developed urban areas of Kobe-city and its environs in the Kansai area of Japan. Central and local governments were confused in their responses to this disaster for a certain time after it occurred. There were delays in gathering disaster information, providing first aid and rescue services, and fire fighting against multiple fire outbreaks. Furthermore, the lifeline restoration was delayed due to disorderly traffic congestion and conflicting recovery constructions. There were also information bottlenecks in aiding victims' lives, such as operations of shelters, debris removal, etc.

From the lessons learned, the Japanese government and the major local governments have prepared their own disaster management information systems to handle suddenly occurring natural disasters. But, these

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systems are, sort of, first generation system. In 2002 the Ministry of Education, Culture, Sports, Science and Technology of the Japanese Government started assigned project to mobilize leading-edge information technology to develop the second generation system, which is called as the Integrated Earthquake Disaster Simulation Systems [1].

The system being developed in this project utilizes the rapidly advanced information technology (IT) to develop a drastically improved system. In other words, utilizing frontier IT, the project aims at developing a system to realize smooth implementation for municipal governments, to ensure ease of use and to realize an advanced quantitative disaster assessment that is useful to optimize disaster response activities. The system deals with many simulators related to the earthquake disaster and its time-domain progress as well as the disaster recovery processes in a comprehensive manner. It totally simulates the disaster and the human responses.

## **BASIC CONCEPTS AND KEY TECHNOLOGIES FOR THE DEVELOPMENT**

The basic ideas for this development are summarized as follows:

- (a) The system shall be not only highly-functional but also inexpensive and robust.
- (b) The system shall be linked seamlessly with daily operations of municipal governments.
- (c) The system shall realize the individual and high-precision damage estimation of structures.
- (d) The system has to predict progression of a disaster and response efficacy faster than the real time progress.
- (e) The system shall assist municipal governments not only in emergency operation but also in recovery and reconstruction operations. The system shall also be utilized in the preparedness phase, such as the emergency professionals training, the evacuation plan verification, etc.

The key technologies for the system are as follows:

- (a) The Risk Adaptive Regional Management Information System (RARMIS) proposed by Kameda [2]
- (b) The Spatial-Temporal GIS with the open data structure and the open specification of application program interface [3]
- (c) The damage estimation based on the dynamic response and the deformation capacity of individual structures [4]
- (d) The multi-agent model simulation [5]
- (e) The large scale distributed simulation environment [5]

## **HIGHLY-FUNCTIONAL, INEXPENSIVE AND ROBUST SYSTEM**

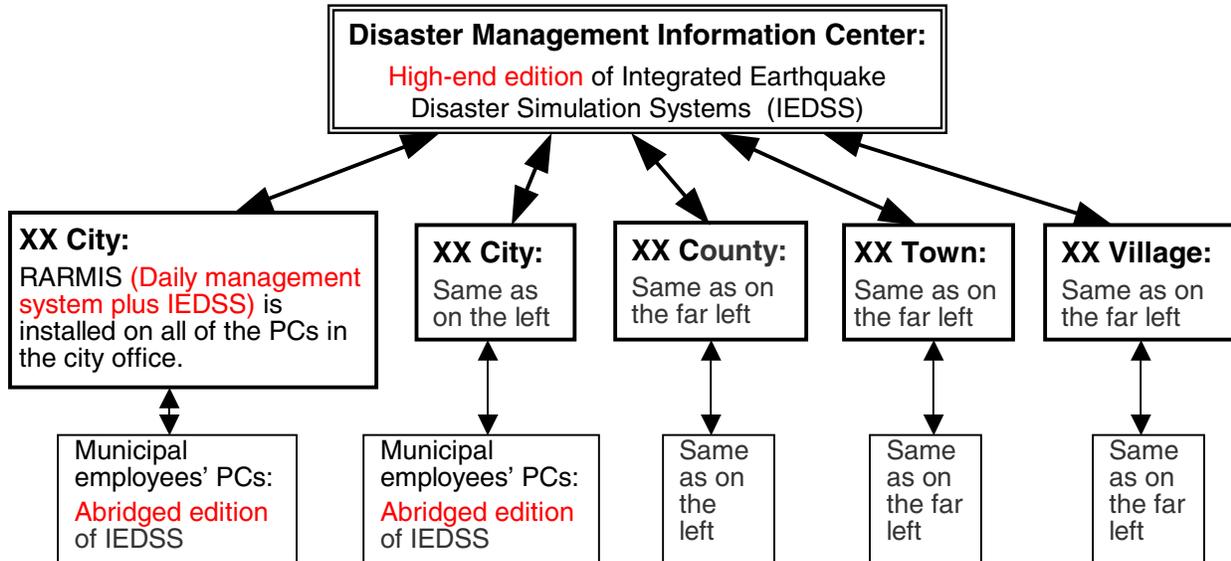
### **Hardware**

The system shares personal computers with the daily management system of the municipal government. This sharing ensures smooth handling of computers even in the case of emergency and avoids the technology obsolescence of computer hardware. The system conforms to the disaster management information center [6], which is shared by many municipal governments and reduces their administrative costs drastically (Figure 1). The disaster management information center also plays a vital role in the system backup in the case that a destructive earthquake damages the information system placed in individual municipal government.

### **Software**

As the development is supported with a public fund, the middleware and the application softwares will be inexpensive for public use. The data structure and the application program interface will be opened to the public so as to promote free competition among software houses in the developments of application

programs. The system is designed to conform to be decentralized independent and is expected to be installed to all of the personal computers in municipal governments. Even if the communication among PCs and/or servers is lost, the stand-alone computer continues to provide the minimum but the necessary supports with the decentralized independence system loaded on it.



**Figure 1. Decentralized independence system supported by Disaster Management Information Center**

### SEAMLESS LINKAGE WITH DAILY OPERATIONS

Most of the earthquake disaster management information systems currently used by municipal governments are the dedicated systems for the disaster management. As the earthquake disaster occurs infrequently and suddenly, the dedicated system will be operated in complete chaos and tend to be brain-dead. Moreover, the database of stand-alone systems ineluctably falls behind the change of the real world, because it needs data maintenance, which will cost excessively for municipal governments. On the other hand, Kameda [2] proposed an idea named Risk Adaptive Regional Management Information System (RARMIS), which links the disaster management information system seamlessly with the daily operation information systems of municipal governments. The importance of this idea is that those systems use a common database and share the computer resources in the municipal government.

Figure 2 and 3 are conceptual diagrams of the RARMIS. In the daily operation phase, the field offices of municipal governments receive information who is born, who is dead, where a house is built, where a road needs to be repaired, etc. These information are keyed-in to computers and stored in the common database constructed on the Spatial-Temporal GIS (the details appear later) every day. Soon after that a destructive earthquake hits the area, the RARMIS in the municipal government shifts from the daily management mode to the disaster management mode automatically. Then, the disaster management information system on the RARMIS runs using the common database, estimates the seismic intensity and the distribution of damages, and displays their mappings on the same computers used in the daily operations. The information assists rescue professionals, fire brigades, emergency recovery staffs etc. in doing their missions. The duty experts at the disaster management information center operate the disaster progression simulation to find out the optimum strategy for search and rescue, fire fighting, recovery logistics, etc.

Concurrently, damages and their progressions are recorded on the Spatial-Temporal GIS as the space changes in time.

After the emergency phase, the disaster management information system shifts to the recovery phase seamlessly, and continues to produce support information such as shelters, logistics of daily commodity, transportation of rubble, restoration of basic infrastructure etc. These recoveries are also recorded on the Spatial-Temporal GIS as the space changes in time.

Then, the system shifts to the reconstruction phase. A system, something like a city planning support system, runs on the RARMIS, using the Spatial-temporal information stored in the common database effectively. The reconstruction phase gradually returns to the normal daily operation.

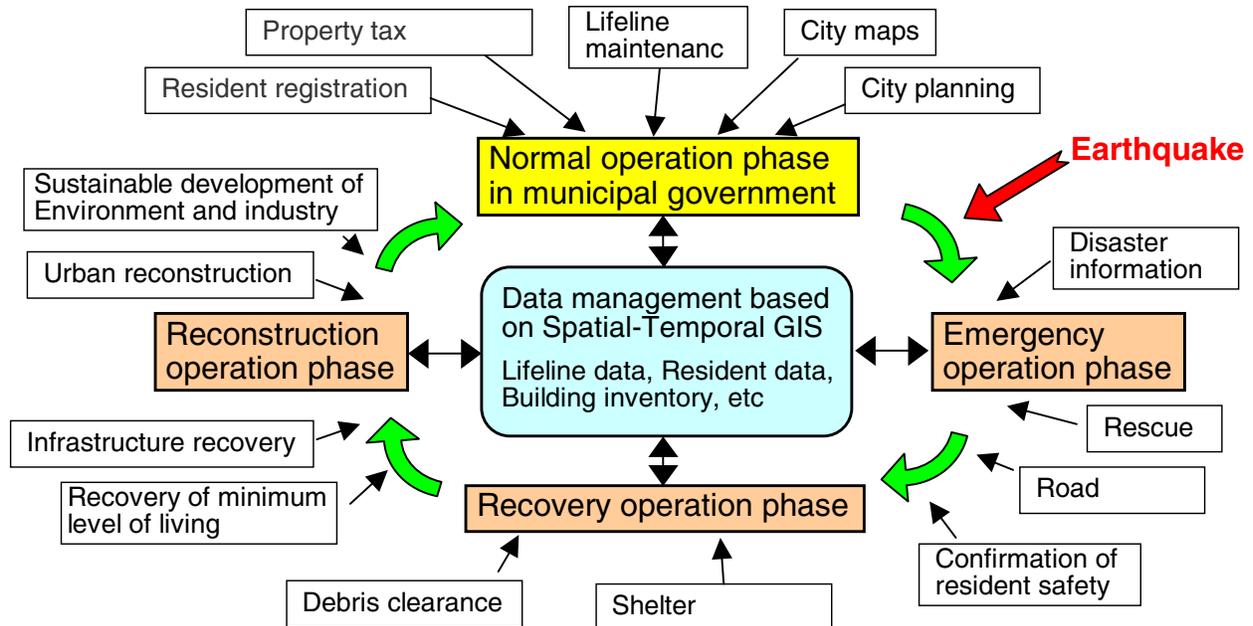


Figure 2. Functions of the Risk-Adaptive Regional Management Information System

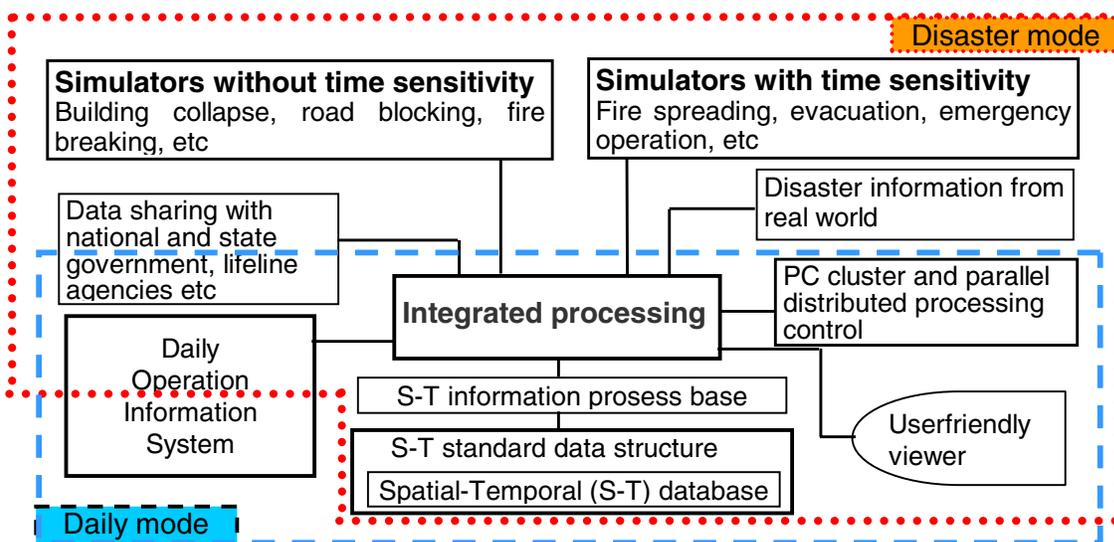


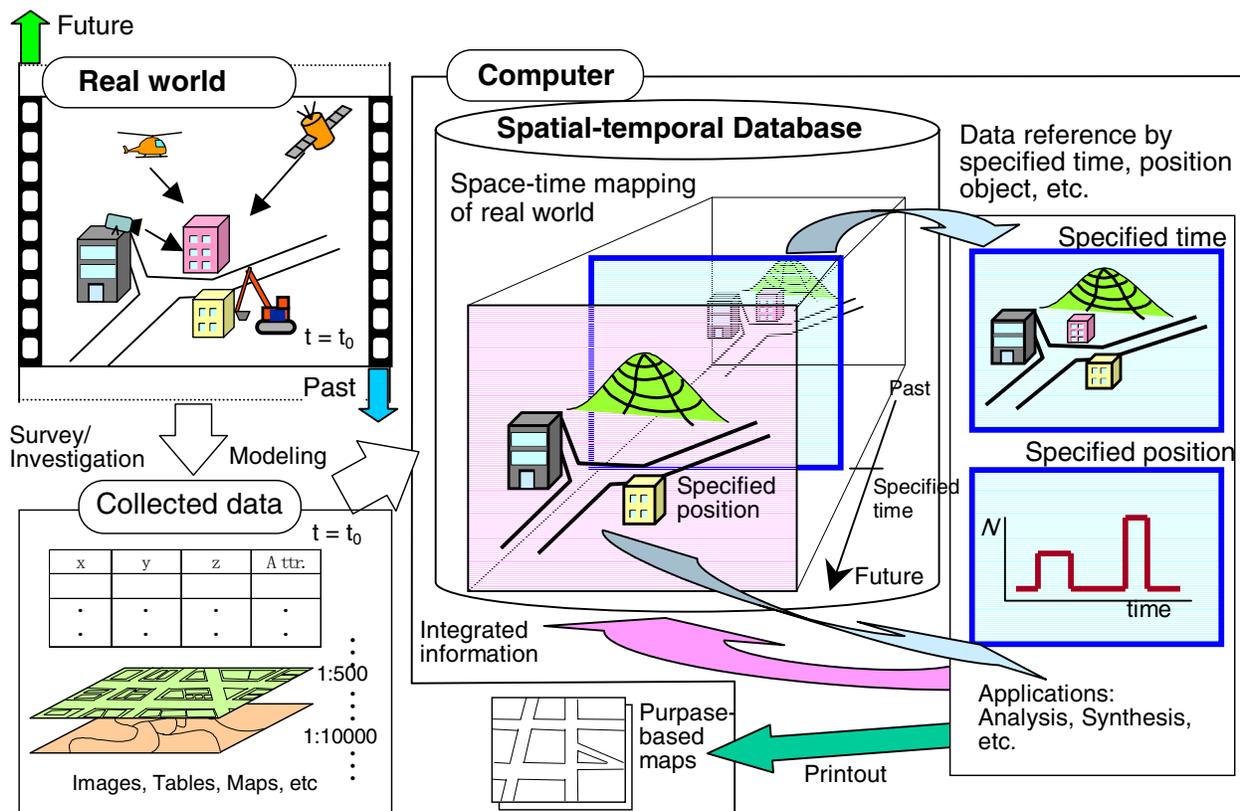
Figure 3. Outline system chart of the Risk-Adaptive Regional Management Information System

## Spatial-Temporal GIS

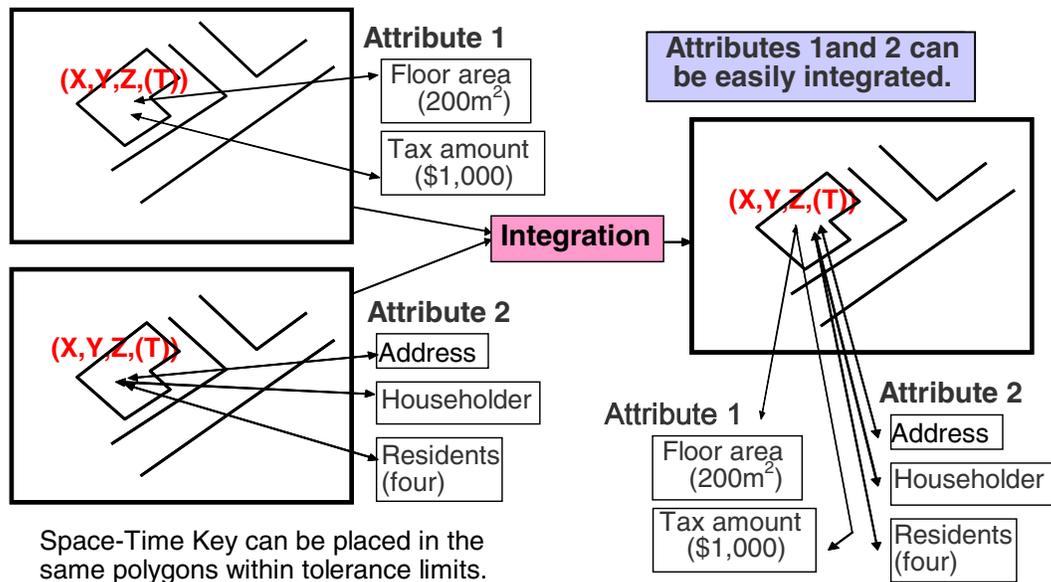
The spatial-temporal geographic information system (Spatial-Temporal GIS) is the foundation of the RARMIS as mentioned above. This innovative technology was developed and established after the Great Kobe Earthquake Disaster [3]. The system is structured with a four-dimensional database which has the time axis in addition to the three-dimensional map information. It can treat the map information, which drastically changes during the earthquake disaster out-break, and subsequent restoration and reconstruction in a united way. Every data on the three-dimensional map has a time parameter as illustrated on Figure 4. This technique realizes four-dimensional database without expanding data size so much and without excluding vague time information. If you specify an instance of time, you can get a three-dimensional map and all attributes pasted on it at that instance. If you specify a point in the three-dimensional map, you can get the time-history of the attributes pasted on that point.

Another advantage of this system is the space-time key system. As most of the data handled by municipal governments can be identified with the place and the time of its origin, the space and time coordinate can be a convenient and universal key column of the data tables in municipal governments. In practice, representative areas inside polygons on a digital city map, for example, the areas inside the outline of houses, are identity keys of the data sets which describe the polygons themselves and their attributes (Figure 5).

The space-time key system makes it easy to realize not only the map-base data retrieval system but also the map-base data integration system. Even among the different kinds of maps, the data mining and the data integration can be easily done as far as the global coordinate and the universal time are commonly used.



**Figure 4. Overall concept of the Spatial-Temporal GIS**



**Figure 5. Map-base data retrieval and integral with the Spade-Time Key system**

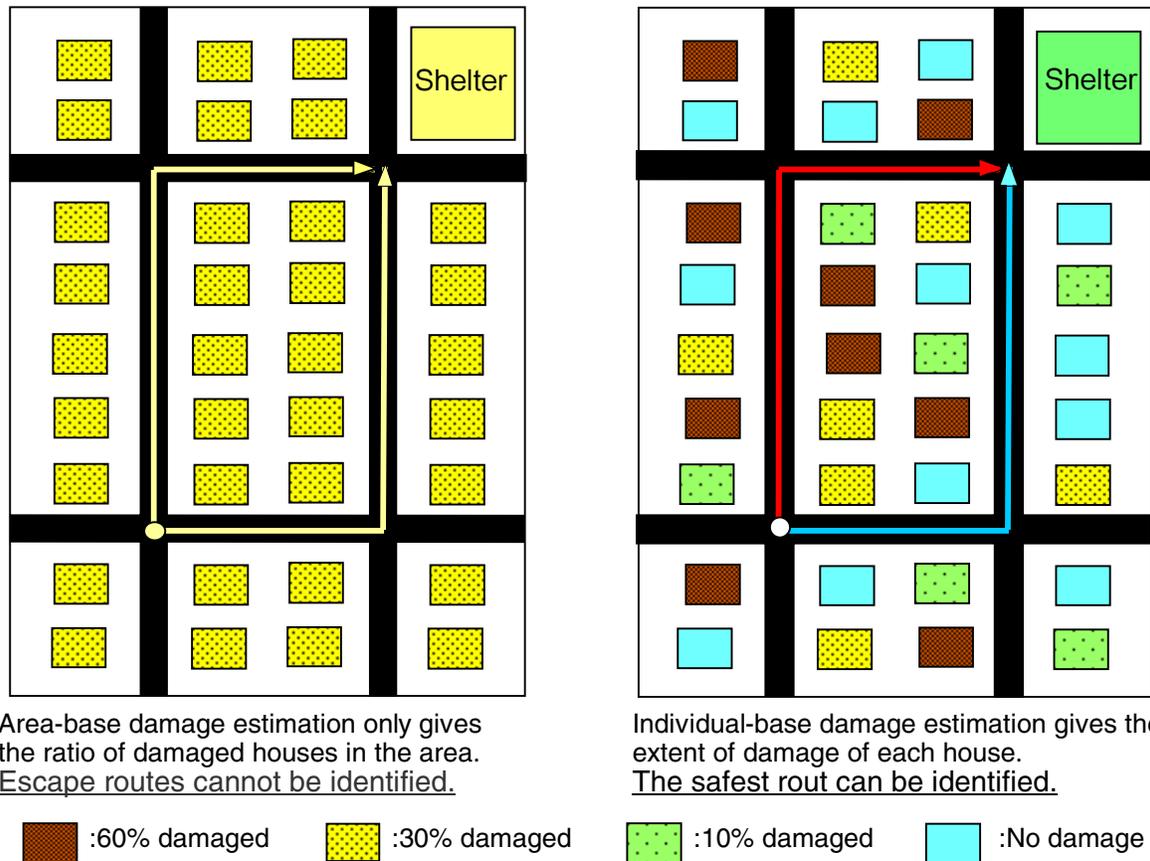
### ACCURATE DAMAGE ESTIMATION OF INDIVIDUAL STRUCTURE

The accurate damage estimation of individual structures is essential to optimize response operations against seismic hazard in both phases of the pre and the post event. Figure 6 is an illustration to explain the importance of the specific estimation of the damage of individual houses. If the damage of the houses is estimated and expressed by the ratio of the damaged ones to all the houses in the area, you can not identify the safest route for the shelter. On the other hand, if the extents of damages of the individual houses are estimated, and even if they are expressed by probability, you can find out the safest route.

The site-specific earthquake ground motion, and the structure-specific dynamic response characteristics and vulnerability are indispensable to this type of estimation.

### Response spectra map of earthquake ground motion

In order to consider the dynamic response characteristics of structures, the earthquake ground motion should be estimated as response spectra. The response spectra map of the earthquake ground motion is established being adjusted to the local soil condition with the precision of 50 meters mesh [7]. The rapid generation of this map is necessary to provide effective information for emergency response within several minutes after an earthquake occurs. However, the ground motion recordings and the subsequent response spectra analysis are not available for all nodes of the mesh, and spatial interpolation of the recorded earthquake ground motions has to be considered. Although the distance between seismographs is sometimes several kilometers or more, the spatial interpolation of the recorded ground motions being adjusted to the local soil condition and the frequency-amplitude-dependent attenuation can estimate the response spectra over the entire mesh of the region concerned.



**Figure 6. Importance of the specific estimation of individual houses**

Prior to the interpolation, the response spectra of the ground motion recordings are corrected to fit to a rock site condition being divided by a frequency-dependent site-specific amplification factor. As the earthquake motion at the ground surface is affected by the amplification characteristics of surface layers, the spatial interpolation is performed at the common rock site condition. The reliable estimation in the spatial interpolation is provided by taking into account the frequency dependent attenuation relation.

The frequency-dependent site-specific amplification factors are determined depending on the response analysis of the surface layers using so called extended-SHAKE [9]. The shear wave velocities converted from popular SPT data are considered to characterize the surface layers and the amplitude dependent non-linearity is also concerned. In practice, site-specific amplification factor matrices which take frequency and amplitude as row and column are prepared in advance.

The response spectrum of the surface of the objective mesh node is generated from the interpolated one being multiplied by the amplification factor. The earthquake ground motion recordings from K-NET and KiK-net [8], and some other seismograph nets are acquired in real time. Some of the recorded seismic waves are transformed into the response spectra at their stations to reduce the telecommunication traffic.

The rapid generation of response spectra map is triggered automatically within the several minutes after obtaining the ground motions at the stations. Initial maps are made from limited number of the real-time components of K-NET and KiK-Net, and they are updated automatically as more data are acquired. The

combination of information from the seismic intensity recording network (2,800 stations in Japan [10]) compensates the map to be more reliable one (Figure 7).

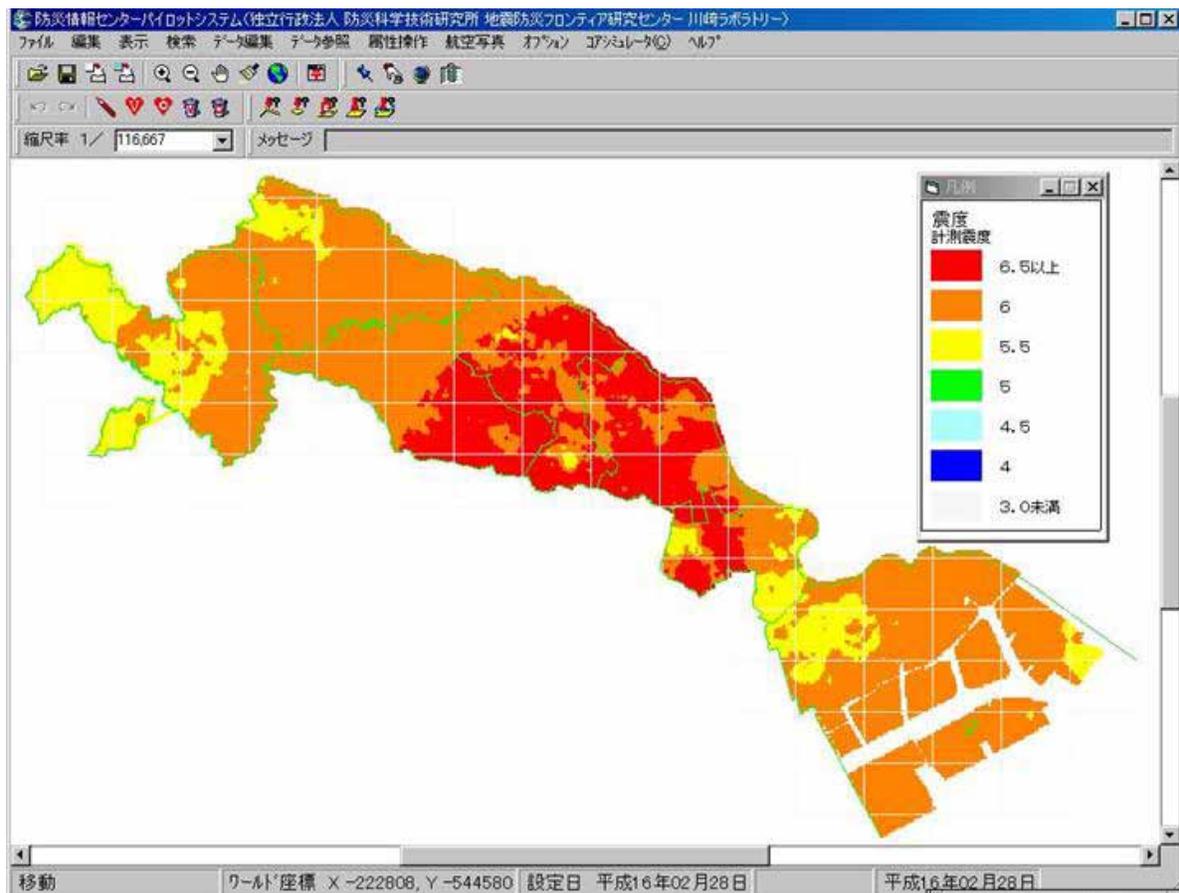


Figure 7. Estimated JMA Intensity map

### Damage estimation based on dynamic response characteristic and deformability of individual structures

The first step of damage estimation of structures may calculate the ratio of damaged structure in an affected area using the fragility curves based on the data of past earthquake damages. But, the second step estimation must be precise and accurate to assist decision-makings of emergency control officers. We are developing and testing the effectiveness of the simulator which estimates the damages considering the structural characteristics of individual buildings, bridge piers, portion of buried pipelines, etc. [9] This method approximately conforms to the seismic design methodology of those structures in Japan. Namely, using acceleration and displacement response spectrum given by response spectra map mentioned above, the dynamic response deformation of structures with the effect of the nonlinearity in load-deformation relation is calculated (Figure 8). Then, in order to evaluate the damage extent, the response deformation is compared with the calibration scale between deformation and damage extent. For example, in case of buildings, the calibration scale of the relationship between the maximum inter-story deformation angle and the building damage level are utilized (Figure 9). The effect of the soil-structure interaction is taken into account when the period and the damping of the structure are specified.

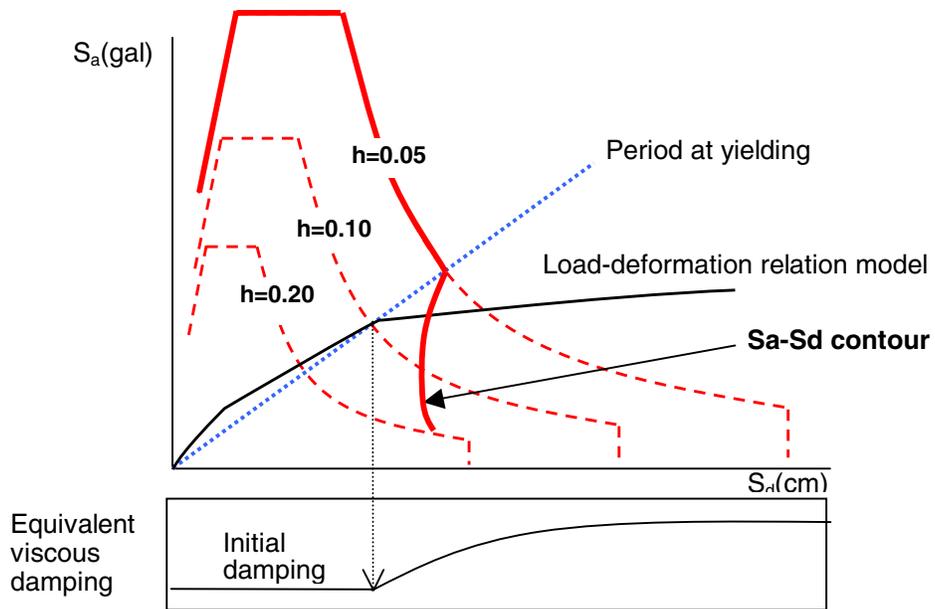


Figure 8. Chart for calculation of the dynamic response deformation of structures considering the load-deformation relation nonlinearity

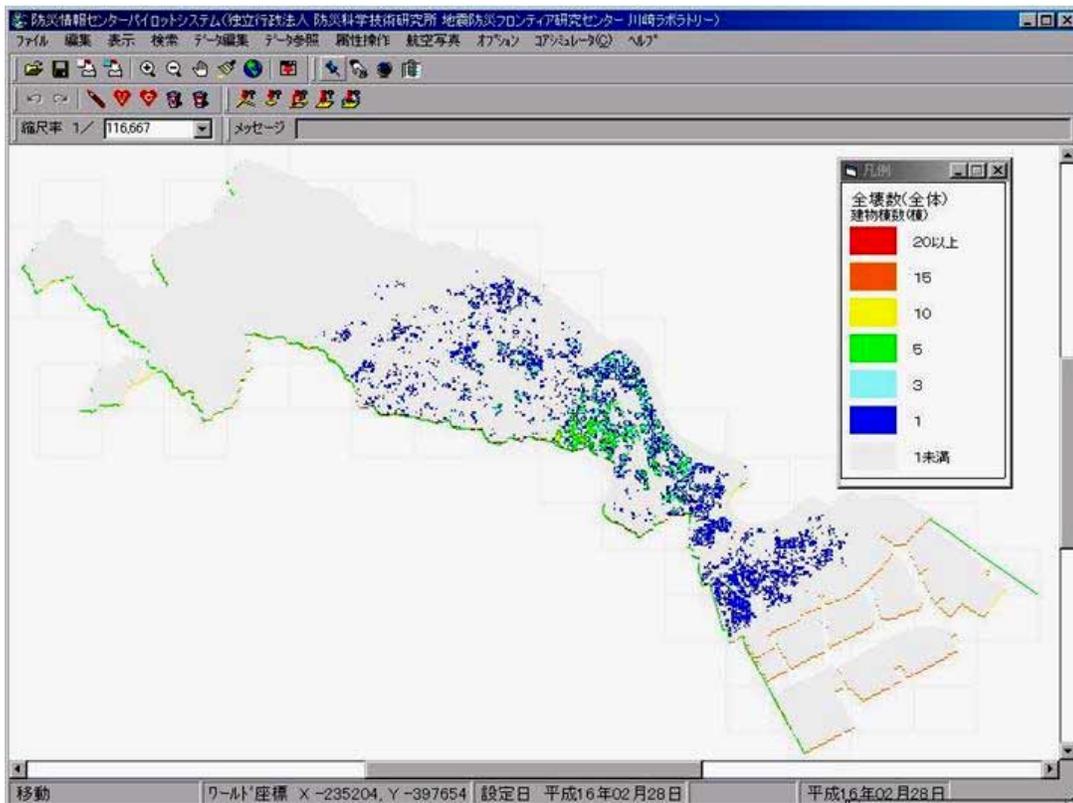
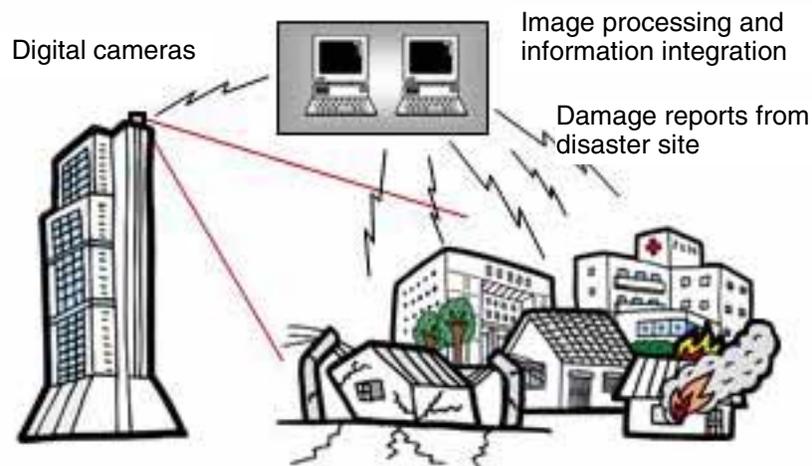


Figure 9. Building Damage estimated with 25m mesh

### Monitoring real disaster

No matter how precisely the damage estimation be done, the precision would remain within the limit of estimation. It is indispensable to include a sub-system which adjusts the estimation with the monitoring data of the real disaster. There are several ways to monitor earthquake damages of urban structures. The satellite remote sensing and/or the airplane mounted camera will be effective tools for the monitoring of wide spread disasters, but they are inadequate for the emergency demand, which may need specific information within one hour. We are developing an on-line fixed-point monitoring system using digital cameras on the top of high buildings (Figure 10). The pictures of the urban area taken at pre- and post-earthquake are automatically compared by the image processing algorithm, and the damage areas are detected and marked out on a digital map. This partial but concrete information of real damages amends the overall damage estimation mentioned above. We are also developing a digital camera system suspended from a temporarily elevated balloon.



**Figure 10. On-line monitoring system using digital cameras**

### SIMULATION OF DISASTER PROGRESSION INTERACTING WITH HUMAN ACTIVITIES

The information system which will actually assist the decision-making of emergency-response agencies must predict not only the progression of the disaster but also the efficacy of the emergency professional activities, such as fire brigades, ambulances etc., faster than the real time progress. If this kind of prediction is completed ten times faster than the real time progress, five strategies of the emergency activities may be virtually tried to find out the most effective one.

Moreover, by simulating the activities of emergency professionals in advance, we can predict the effectiveness of their predetermined guidelines for decision and action. And by simulating the actions taken by citizens under a virtual earthquake disaster, we may be able to find a bottleneck for safe evacuation, which will be taught to every citizen in disaster preparedness education.

As the agent model simulation has a potential to meet these needs, we are developing the multi-agent model simulation system and the large scale distributed simulation environment [5]. Although the development is on the way, we dare to introduce the principles as follows:

### Multi agent model simulation

The primary earthquake damages, such as building collapses, bridge pier tilts etc., may happen almost instantly, but fires may quite easily start here and there in the Japanese city, and then spread over the city at a certain speed in the dense urban environment. This kind of secondary damages can also be estimated by running appropriate simulators. However, fire fighters and other agents do their best to extinguish fires although they may not have enough fire-plugs or cisterns, or they cannot easily access to fires prevented by blockage of roads. Victims do not stay at dangerous area and they move toward would-be-safer area. Mass evacuation may itself cause another kind of secondary damages, for example, in a crowded space such as underground shopping mall, or by a groundless rumor if peoples have been disconnected from right information sources. It is necessary to include relevant human activities in the disaster simulation system to estimate more accurately how a disaster causes secondary damages and to plan how the damages should be reduced. These sorts of simulations will be best performed by agent-oriented programming, because every human or agent can be modeled in a more realistic and detailed manner than other ways of mathematical modeling (Figure11).

Multi-agent programming approach is expected to model individual human activities, by regarding individual human as independent agent that is simulated by its own modeling program. There will be a huge number of agents in the simulator, each of which interacts with others and with its environments, so that enormous amount of information exchange will be needed. Such a huge number of agents itself, say, at least 10,000, as well as the requirement for simulation speed, raises a challenge from the viewpoint of computer science.



- × : Road blocking    ● (with x) : Road re-open work    ⊙ (with x) : Ambulance
- (green) : Not injured citizen    ● (yellow) : Injured    ● (black) : Death    □ (yellow) : Catch fire    □ (brown) : Blazing    □ (blue) : Extinguished

**Figure 11. Multi-agent model simulation on fire fighting and rescue operations**

As can be easily understood, the system should be implemented on the basis of a large-scale high-performance computer system. It should also be cost-effective, so that a PC cluster would be the best choice of the hardware architecture. The average local government office cannot maintain such a big PC cluster and it should be put at the disaster management information center mentioned earlier.

### **Large scale distributed simulation environment**

The multi-agent simulators are in principle distributed to a number of divided regions of a digital map in order to obtain space scalability. That is, the city is divided into small enough regions on which the simulation can run with a performance ten times faster than real time. This division also raises another challenge from the viewpoint of computer science.

## **OTHER DISTINCTIVE FEATURES OF THE INTEGRATE EARTHQUAKE DISASTER SIMULATION SYSTEM**

### **Database preparation strategy**

It is necessary to assess that the readiness of data required for disaster estimations changes with municipality by municipality. It is usual for the data readiness to vary from fine to coarse with urban and non-urban areas even in the same municipal area. Depending the database readiness, usable disaster simulators change, so the accuracy of the simulation changes. However, large capital expenditure and long time are necessary to prepare the database. Thus, the relationships among the level of database readiness, the methodology for combining the simulators, and the accuracy of the damage estimation are proposed. Additionally, a support system is provided to select the most appropriate combination of the simulators and to convince stakeholders to expedite the required database preparation.

### **Real-time earthquake ground motion estimation system**

The hypocenter and magnitude are instantaneously located from the P waves observed near the hypocenter utilizing the seismograph network, KiK-net and/or JMA-net, which is currently developed all over Japan. The intensity of the earthquake ground motion is predicted in succession and the alert is given to the municipal governments before the principal shear wave reaches the subject areas [11]. This alert triggers the switching of the RARMIS from daily mode to disaster mode. It also triggers the emergency management system for fire fighting, water supply systems and so on, and the alert transmittal to citizens, etc. Afterwards, the intensity distribution of earthquake motion is re-estimated basing on the seismograph data in the subject areas when the principal wave reaches. Furthermore, the spectrum information of the earthquake waves is analyzed and transmitted to the response spectra map system mentioned earlier.

### **Simulators incorporated in the Integrated Earthquake Disaster Simulation Systems**

Many kinds of disaster simulators are incorporated in the total system. To simplify additions and improvements, individual simulators are developed according to the protocols and architectures enabling plug-in to the total system. The development progresses step by step, and the following simulators have been plugged in.

#### *Building damage simulator*

Two kinds of simulators are incorporated. The first one is a normal and simple simulator based on the relation between seismic intensity and fragility. This type of simulators is in lower accuracy, but does not require detail database and long computational time, and is useful for the first step estimation and for the poor database readiness districts.

The second one estimates damages using the database concerning building structure, age and height on a building-by-building basis. The method is outlined earlier in this paper.

#### *Road blocking simulator*

Road blocking due to building collapse is estimated from the relative locations of damaged buildings and roads.

#### *Human damage simulator*

Damage to the people who live or work in buildings, shopping centers, terminals, etc. is estimated according to the seismic intensity and the fragility relations.

#### *Fire occurrence and spread simulator*

Fire occurrence is estimated from the damage extents, structural materials (wooden or not) of buildings, together with the time and the season. Furthermore, fire spread is estimated from the house population density, wind force and direction with dryness, and fire fighting level.

#### *Lifeline damage simulator*

Damage to buried lifelines is estimated from the response velocity and/or response strain of the ground during the earthquake concerning liquefaction, micro-topography information and characteristics data of the structures.

#### *Road and railway damage simulator*

Damage is estimated for rout on cut and filled ground, tunnel, station, etc. on the base of the seismic intensity and fragility relations. In the case for bridge piers, a pier-by-pier base damage simulator is installed. This simulator estimates the response deformation of the pier and compares it with its deformability, which is evaluated using the database concerning pier structure, height, and material strength beforehand.

#### *Slope failure simulator*

Damage is estimated for natural slopes, artificially formed slopes, etc. on the base of the seismic intensity and fragility relations.

#### *Simulator for industrial facilities*

A system to simulate diffusion of inflammable material, fire spread and explosion disasters in chemical plants is installed.

## **CONCLUDING REMARKS**

This paper discusses the typical features of the Integrated Earthquake Disaster Simulation Systems, which is expected to effectively mitigate the earthquake disaster of the highly-networked information society. The research and development is on going but has been promoted in collaboration with several municipal governments and the following distinctions came out through the collaborated trial operations.

- (a)Municipal employees can key in most of the fundamental data by themselves. The data maintenance cost can be reduced to a considerable level.
- (b)The prospective cost-performance of the system may be accepted.
- (c)The RARMIS concept is excellent but sets rather high hurdle to the municipal government which already has and becomes familiar with some information systems.
- (d)The Spatial-Temporal GIS is effective not only for disaster management but also for data sharing among the national and the municipal governments and their administrative divisions.
- (e)The accurate damage estimation of individual structures and the multi-agent model simulation are effective not only in the post-earthquake emergency relief phase but also in the preparedness phase.

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