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Development of real-time earthquake damage information system in Japan

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Abstract

It is extremely important to quickly assess the damage immediately after an earthquake for providing suitable disaster response. We has constructed prototype of a real-time earthquake damage information system for appropriate decision-making regarding the initial response at an earlier stage immediately after an earthquake by combining amplification characteristic data for subsurface ground as well as basic data such as population and building information and observation data including real-time strong-motion data observed by K-NET and KiK-net. We report on our progress in building a database containing building models covering the entire country of Japan, along with the development of methodologies related to damage estimation and situation assessment, continuous strong motion observation, and system architecture construction, which are necessary components of a real-time earthquake damage information system. This system is intended to assist in making initial response decisions immediately after a disaster, and is expected to estimate and assess the overall condition of damage in real time even in the case of a disaster over a wide area, such as a large earthquake.

Keywords: real-time, earthquake damage estimation, situation assessment, building model, Kumamoto earthquake

1. Introduction

Promptly assessing the damage situation immediately after an earthquake is very important in making appropriate initial response decisions and reacting to the disaster. The Prompt Assessment of Global Earthquakes for Response (PAGER) system was developed and is operated by the United States Geological Survey (USGS) to assess the damage situation immediately after the occurrence of an earthquake anywhere in the world [1]. This system uses earthquake information (at the least the earthquake location and magnitude are necessary) provided by the USGS National Earthquake Information Center (NEIC) within approximately 20 min after an earthquake and predicts a ground motion distribution, which is output as a “ShakeMap” within about 1 min. The seismic motion distribution in this ShakeMap and the population and building distributions are used to estimate the human and economic damage. These estimations are expressed as a probability distribution that takes uncertainties into account. An alert on a four-level scale is issued, and “onePAGER,” a summary of the estimation results, is made available on the Web.

In Japan, the importance of promptly assessing the damage situation, integrating information during the preparation phases, taking emergency measures, recovery, reconstruction, and prompt comprehensive decision making was again pointed out after reviewing the emergency measures taken after the Great Hanshin-Awaji earthquake in 1995. As a result, the Cabinet Office develops and operates the Disaster Information Systems (DIS) and Early Estimation System (EES), a subsystem for the early estimation of earthquake damage. These systems utilize the Geographic Information System (GIS), which manages landscape, ground, population, building, and disaster prevention facilities [2]. The damage estimation by EES for the West Tottori Earthquake in 2000 was about 8,000 collapsed buildings and around 200 deaths, whereas the actual damage was about 400 completely destroyed buildings and zero deaths. This huge discrepancy shows many issues with the distribution estimation of the exposure to earthquake hazards and the difficulty of damage estimation.

Based on this background, the “Reinforcement of resilient function for preventing and mitigating disasters” was selected as a Cross-ministerial Strategic Innovation Promotion Program (SIP) project. The National Research Institute for Earth Science and Disaster Resilience (NIED) is taking the lead in the research and development of a real-time earthquake information system for damage estimation and situation assessment. This system is intended to assist in making the initial response decisions immediately after a disaster, and is expected to estimate and assess the overall damage condition in real time, even in the case of a disaster over a wide area, such as a large earthquake. Moreover, the system aims to provide detailed estimations to provide information at the small-district-to-individual-building level. Here, we report on our progress in compiling a database containing building models covering the entire country of Japan, along with the development of methodologies related to damage estimation and situation assessment, continuous strong motion observation, and system architecture construction, which are core components in the research and development of a real-time earthquake damage information system.

2. Building models covering all of Japan for earthquake damage estimation

The building models were compiled using residential map data created through field surveys covering almost all of Japan. Building models with the attributes necessary for damage estimation, which include the building construction class and construction year, were generated for each 250-m square mesh. The complete model covers approximately 56 million buildings, and the precision was enhanced based on the method [3], which is described below.

The building construction is estimated using the construction-type information of each building in the residential map data. Buildings are categorized into residential buildings (detached houses and apartment buildings) and industrial buildings (commercial facilities and office buildings), and the structure is estimated (wood, steel, or reinforced concrete). The building data of buildings for rent without residents, as extracted from the residential map data, contain the business category from the corporate telephone number information, along with the business type of the building, number of floors, and estimated construction class of “not wood.” The business category is estimated using Tables 32, 35, and 60 of the 2008 Corporate Building Survey and the number of floors of each business category. The construction classes available in private real estate information (about 1.7 million buildings) are categorized into wood, steel, and reinforced concrete. The real estate information and residential map data are associated and processed using the attribute type, number of floors, and area. The structure category is determined according to Table 1, based on the processed data and the 2008 Housing and Land Survey. For “named buildings with no information on number of floors” and “unnamed buildings,” the structure category is determined using real estate information if available. The structure category of “named buildings with no information on number of floors” without real estate information is derived based on the building area. The attribute type of “unnamed buildings” (objects and detached houses) is determined to be named objects and private housing. However, detached houses with building areas greater than 200 m2 are considered to be “collective housing” in the category of detached housing in the real estate information, and the construction class is considered to be “steel.” Moreover, the “unnamed building” category with attribute type “general building” and no information on the number of floors is estimated based on the use zone at the position of the building, and an algorithm is used to derive the building class. Fig. 1 shows a comparison of the number of buildings by building structure category estimated using residential map data and the number of buildings in municipalities according to fixed asset summary records for 2013. The two data sets are consistent.

The estimation of the number of buildings by construction year is carried out using the 19 construction year categories in “Table 38, survey of houses by construction year” in the fixed asset summary records. “Wooden houses” and “non-wooden houses” are described using the floor space in “Table 38, survey of houses by construction year.” Therefore, the floor space by construction year values are aggregated into seven categories (Table 2), and the ratio of the floor space per category to the total floor space is calculated. The survival rate for each of the seven categories is obtained for each municipality, and this survival rate is used to estimate the number of buildings by construction year in the 250-m mesh in each municipality. The areas affected by the tsunami during the Great East Japan Earthquake are estimated separately using the building damage condition information from the Archive of Recovery Support Survey [4], where flooded regions are categorized by areas with similar damage.

Table 1 Structure category decision chart

Attribute type		Number of floors	Area per building	Structure category
Unnamed	Object	2 or less	—	Reinforced concrete
	Detached house		Less than 200 m2	Wood
	—		200 m2 or more	Steel
Named	Object	2 or less	Less than 80 m2	Wood
		1 or more	—	Reinforced concrete
	Building for rent	2 or less	Less than 150 m2	Wood
			150 m2 or more	Steel
		3 or 4	Less than 50 m2	Steel
			50 m2 or more	Reinforced concrete
		5 or more	—	Reinforced concrete
	Collective housing	1	—	Wood
		2	Less than 200 m2	Wood
			200 m2 or more	Steel
		3	Less than 150 m2	Steel
			150 m2 or more	Reinforced concrete
		4 or more	—	Reinforced concrete
	Housing of individuals	2 or less	—	Wood
		3 or more	Less than 50 m2	Wood
			50 m2 or more	Reinforced concrete
	Offices	2 or less	Less than 50 m2	Wood
			50 m2 or more	Steel
		3	—	Steel
		4 or more	—	Reinforced concrete

Table 2 Construction year categorization of building

Category	Construction year in fixed asset summary records
Category 1	Ratio of buildings built prior to Jan. 1, 1963
Category 2	Ratio of buildings built between Jan. 2, 1963, and Jan. 1, 1972
Category 3	Ratio of buildings built between Jan. 2, 1972, and Jan. 1, 1981
Category 4	Ratio of buildings built between Jan. 2, 1981, and Jan. 1, 1990
Category 5	Ratio of buildings built between Jan. 2, 1990, and Jan. 1, 2002
Category 6	Ratio of buildings built between Jan. 2, 2002, and Jan. 1, 2011
Category 7	Ratio of buildings built between Jan. 2, 2011, and Jan. 1, 2014

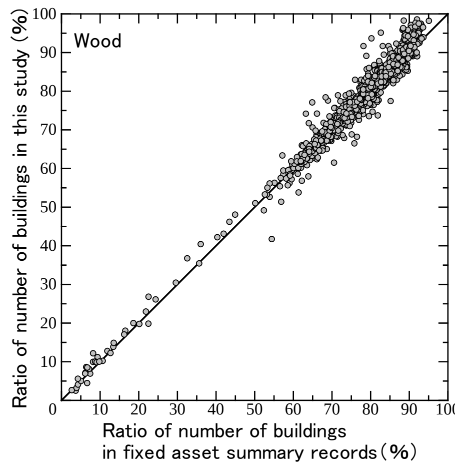

Fig. 1. Comparison between ratio of number of wooden buildings by fixed asset summary records for fiscal year 2013 and this study for each municipalities

3. Development of seismic motion, building damage estimation, and situation assessment methodologies

3.1 Estimation of seismic motion

Information on the seismic motion, which is input to the assessment point, is necessary to assess building and human damage. However, in most cases, there is no measurement point close to or on the ground that can be considered to be equivalent to the assessment point. Therefore, the spatial distribution of seismic motion must be estimated using the seismic motion at the observation points. Here, the spatial distribution estimation is performed by converting the seismic intensity data measured at the ground surface to the peak ground velocity (PGV) using an empirical formula. The peak velocity of the engineering bedrock is estimated considering the site amplification factor of each measurement point. Then, interpolation is used to obtain the spatial distribution, and a two-dimensional estimation is conducted by again multiplying the amplification factor.

In other words, the measured seismic intensity is converted to the PGV using the formula [5]. Next, the peak velocity of the engineering bedrock is derived by dividing the obtained PGV by the amplification at the ground surface. This amplification is based on the average shear-wave velocity in the upper 30 m (AVS 30), according to the 250-m mesh map of the geomorphologic classification covering all of Japan, and the empirical formula between the amplification and AVS30 is applied [6]. The peak velocity of the engineering bedrock immediately below the measurement point, as obtained above, is spatially interpolated using Delaunay triangulation onto a 250-m mesh. Then, the PGV is estimated by multiplying the amplification, and the two-dimensional distribution of the seismic intensity is derived.

The seismic intensity is a basic seismic motion index that can be obtained from a national measurement network, and is adopted as input information for many damage functions. However, the building damage condition is significantly different under the same seismic motion in many cases. Thus, the damage cannot be simply described by the seismic intensity and earthquake resistance of buildings. Therefore, an index is proposed that takes the seismic motion period band into account, which is more closely related to the building damage [7]. We conduct a high-precision seismic-motion estimation (e.g. PGA, PGV, SI, response spectrum) that considers the seismic motion period band based on the wide area underground structure model under construction for the Kanto and Tokai regions in Japan.

3.2 Estimation of building damage

Damage estimation is carried out by providing the estimated seismic motion as an input and applying a damage function to the building model described in section 2.
Damage rates are then calculated from estimated ground motion using the following fragility curve by structure, observed Building Standard Act, and damage level, i.e., completely or partly destroyed:

$$\mathrm{P(PGV)} = \Phi\left(\frac{lnPGV-\lambda}{\zeta}\right) \tag{1}$$

$$\mathrm{P(I)} = \Phi\left(\frac{I-\lambda}{\zeta}\right) \tag{2}$$

$$\Phi(x) = 0.5\left(1 + erf\left(\frac{x}{\sqrt{2}}\right)\right) \tag{3}$$

P (PGV) is the damage rate with PGV as input, P (I) the damage rate with a measured seismic intensity of I as input, Φ the standard cumulative distribution function, λ and ζ are parameters that change depending on structure, building age, and damage level, and erf an error function. The rate of completely destroyed buildings is 0 under an intensity corresponding to 5 upper or less and that of completely and partly destroyed buildings is 0 under an intensity corresponding to 5 lower or less. Previous study has proposed multiple fragility curves based on various data sets. The real-time earthquake damage information system applies multiple fragility curves to each structure type as shown in Table 3.

Number of damage buildings N by damage level in each mesh is estimated from the damage rate in each mesh obtained above using the following equation:

$$N_{m,k} = \sum_i \sum_j P_{m,i,j,k}\, T_{m,i,j} \tag{4}$$

where m is the mesh number, k the damage level, i the type of building, j the observed Building Standard Act, N the number of damage buildings, P the damage rate, and T the number of buildings in meshes. The damage rate of buildings is also calculated as damage rate of all buildings R based on the number of buildings in each mesh using the following equation:

$$R_{m,k} = N_{m,k} / \sum_i \sum_j T_{m,i,j} \tag{5}$$

Day or night population data are used depending on the time an earthquake occurs. Day population data is based on the 2010 censuses and subdivides original 500-m mesh data into 250-m mesh data. Estimation results for building damage and population exposure to seismic intensity in each mesh is aggregated by municipality or prefecture.

Table 3 Building damage estimation methods available in the real-time system

Method	Structure	Reference
method1	Wood	Cabinet Office(2012)[8]
	Reinforced-Concrete	Cabinet Office(2012)[8]
	Steel	Cabinet Office(2012)[8]
method2	Wood	Horie(2004)[9]
	Reinforced-Concrete	Murao and Yamazaki(2002)[10]
	Steel	Murao and Yamazaki(2002)[10]
method3	Wood	Horie(2004)[9]
	Reinforced-Concrete	Murao and Yamazaki(2000)[11]
	Steel	Murao and Yamazaki(2000)[11]
method4	Wood	Murao and Yamazaki(2002)[10]
	Reinforced-Concrete	Murao and Yamazaki(2002)[10]
	Steel	Murao and Yamazaki(2002)[10]
method5	Wood	Cabinet Office(2004)[12]
	Reinforced-Concrete	Cabinet Office(2004)[12]
	Steel	Cabinet Office(2004)[12]

3.3 Assessment of damage situation

The damage function statistically links the seismic intensity to the damage ratio using past earthquake damage information, and there may be estimation errors when applied to individual earthquake damage. On the other hand, in the SIP project, information on the damage situation may be extracted through an analysis of images from earth observation satellites, summarized from an analysis of social media, and actually obtained by an on-site investigation by municipalities. The actual damage information is highly accurate, but both temporally and spatially fragmental and is not always effective in the early assessment of the total damage. Therefore, we are investigating methods to improve the damage estimation accuracy or confirm information using a Bayesian updating method for the damage estimate information with actual damage information to quickly and accurately assess the damage situation.

The entire damage picture is assessed using a Bayesian update of the quick estimation with fragmental actual damage information. Another study performed Bayesian updating based on a partial damage investigation for an entire region, where the seismic intensity and damage ratio were considered uniform [13]. However, this study updates the estimation error, a parameter in the damage function, instead of the damage ratio, to quickly assess the entire damaged area using information on regions with different seismic intensities and damage ratios. Fig. 2 shows the flow of the method used to reflect the actual damage information in the estimated information using Bayesian inference.

Simulations are carried out on the method for assessing the entire damage picture through the integration of actual damage information using Bayesian updating. The simulations consider a damaged area of 25 districts, each of which have 20 meshes (total 500 meshes) and contain four types of buildings with different earthquake resistance values. The number of damaged buildings needs to be reported for each district.

Fig. 3 compares the “true number” (blue) and “simulated number” (red) at each stage for the damaged buildings in each district. The “true number” is derived by first arbitrarily categorizing each mesh into g1, g2, and g3. A seismic intensity is designated for each mesh based on a random measured intensity number, which is normally distributed, with an average of 5.5 and a variation coefficient of 0.3. A value of 0.3 is subtracted from this number for the g1 meshes and added to it for the g3 meshes. This reflects an uneven distribution of seismic intensity for the region, and g1 to g3 are schematic representations of the surface subsoil. The numbers of the four types of buildings in each mesh are randomly set. The damage functions of these buildings are considered to be expressed by a normal distribution with the parameters listed in Table 3. The damage ratio and number of buildings are multiplied for each building type and each mesh and then summed up in each district.

Next, the error compared to the “true number” is regarded to arise from the error in the damage function parameters. Therefore, the damage function for the “quick estimation” is designated by uniformly subtracting 0.1 from the standard deviation in Table 4 to represent a general trend and then adding the error estimated by the foundation type and building type listed in Table 5. The number of damaged buildings according to the “quick estimation,” which is obtained in a manner similar to the “true number,” is provided as the “quick estimation” (red) bar graph in the leftmost panel of Fig. 3.

Fig. 3 shows the estimated number of damaged buildings, which is the expectation value of the posterior distribution after the Bayesian updating of the damage function using the numbers of damaged buildings in district 1, districts 1–5, and districts 1–10. The “quick estimate” considers the estimation error, where the average damage function is underestimated when the “surface subsoil” is type g1 or g2 as shown in Table 5. In other words, the total earthquake resistance is relatively underestimated. As a result, the number of damaged buildings is significantly overestimated compared to the “true number” in Fig. 3. However, the estimation error decreases toward the right panel, or when the damage information is integrated starting from district 1. However, this example uses ideal conditions, which ignore the errors in the model from evaluating the damage function with a given function form. Moreover, the statistical properties are known to be normal distributions, and the categorizations in the model are given. We will investigate specific categorizations with strong correlations to the estimation error to allow the efficient integration of information through the use of statistical relations between the ground classification, building characteristics such as construction year, and estimation error in past earthquake damage data.

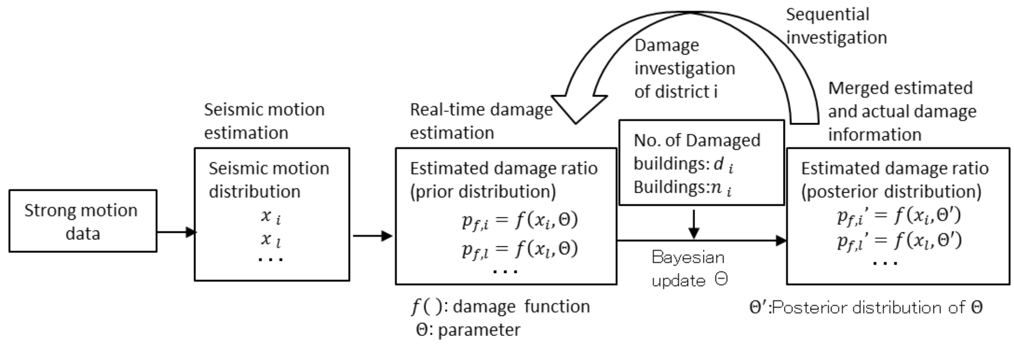

Fig. 2 Flow of integration of estimated and actual damage information through Bayesian updating

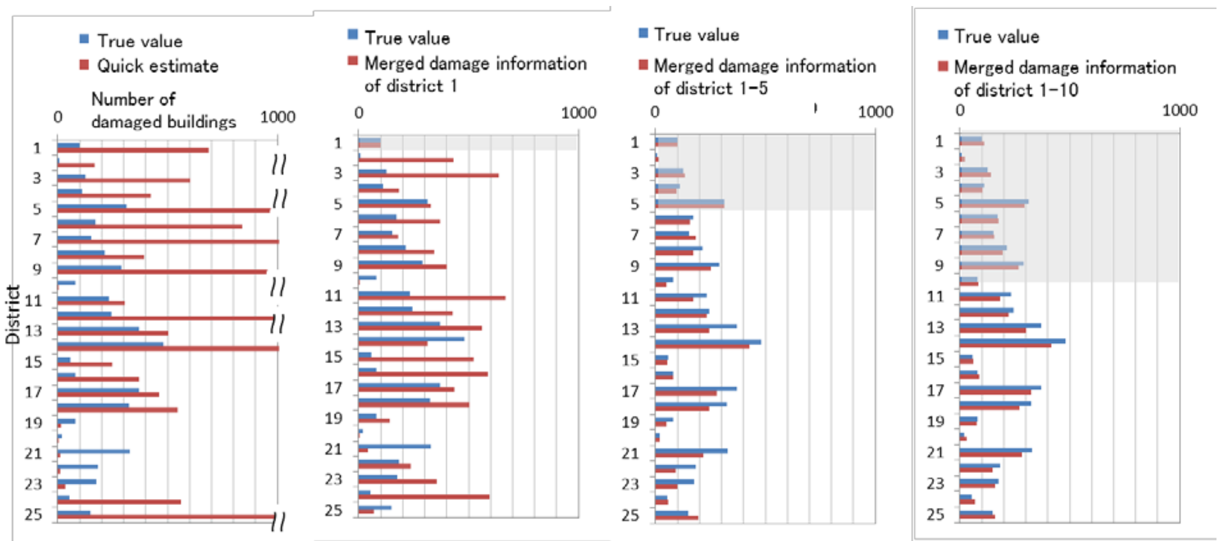

Fig. 3 Simulation results of situation assessment

Table 4 Damage function parameters

Building type	b1	b2	b3	b4
Average	6.25	6.95	6.93	7.5
Standard deviation	0.27	0.44	0.5	0.6

Table 5 Estimation error in quick estimates

		Average	Standard deviation
Total		0	-0.1
Building	b1	0.3	0
	b2	0.1	-0.1
	b3	0.25	-0.1
	b4	0.4	-0.1
Surface subsoil	g1	-1	0
	g2	-0.3	0
	g3	0.2	0

4. Continuous observation of strong motion

Real-time dense strong motion data are necessary for a real-time earthquake damage information system that can output information within a few minutes of the occurrence of an earthquake. Standard public networks such as integrated services digital network (ISDN) lines, which connect and transmit data only in the case of an earthquake, may not be able to establish a connection because of congestion and take at least a few seconds before establishing a connection. These issues can be resolved only through continuous measurement that enables data transfer.

Continuous waveform data transfer is the standard for micro earthquake measurement, and the WIN format, which is a multichannel data transfer format established in the 1990s, has been used as the standard format. The

WIN format is a packet transfer format where analog-to-digital converted waveform data are separated into user datagram protocol (UDP) packets representing one second and one channel. This packet transfer method is a good method to maximally utilize the limited line bandwidth and send continuous waveform data. Furthermore, data from multiple measurement points can be easily branched and transmitted to many users. However, the temporal order of the packets and transmission certainty are not guaranteed. On the other hand, strong motion indices such as the maximum acceleration, response velocity, and real-time seismic intensity are necessary in estimating the damage. Continuous data are necessary in many cases to derive these quantities. Thus, a transmission characteristic that does not guarantee the order and reliability is a huge hindrance in the continuous measurement of strong motion. As a consequence, a streaming transformation based on the transmission control protocol (TCP) is suitable for continuous strong motion measurement for real-time damage estimation. There is no connection concept in UDP-type transmission. In contrast, the TCP type controls the connection between a strong-motion seismometer and data center. Thus, it is always possible to check whether each measurement point can be used in real-time damage estimation.

Since the installation of the K-NET02 strong-motion seismometers in 2003, K-NET/KiK-net, which is operated by NIED, uses a method where a strong-motion seismometer automatically connects to a data center after detecting an earthquake and transmits data. Therefore, this transmission is continuously carried out, and the trigger conditions are always met. This new transmission method has the following features.

-The continuous transmission of the indices of strong seismic motion has the highest priority, and the transmission of waveform data is not the only objective.

-Each strong-motion seismometer transmits to multiple data centers in parallel to secure path redundancy.

-The algorithm to compress the waveform data focuses on reducing the maximum data size.

-The use of lossy compression algorithms is acceptable to increase the compressibility.

-The data duration can be dynamically changed between 0.1 and 1 s for real-time and efficient transmission.

-Various pieces of header information are compressed to reduce the bandwidth needed for transmission.

-The conversion to the strong motion WIN32, WIN32, and WIN formats is possible.

5. Development of real-time earthquake damage information system

We are developing a real-time earthquake damage information system that consists of subsystems that include observation data reception, damage estimation and situation assessment, and information provision. The prototype real-time system based on the J-RISQ system [14] estimates a seismic intensity distribution, population exposed to the seismic intensity, and building damage. These results are provided in the interoperable international standard formats such as the web map service (WMS), web feature service (WFS), and numerical data to allow secondary use by other systems. In addition to providing information to other systems, WebGIS is used to construct a service to visualize estimation results and overlay these on a generic Internet map service. The user selected results are shown as a 250-m mesh map (estimated seismic intensity, PGV, maximum velocity of the engineering bedrock, ground amplification, population exposure to seismic intensity, and building damage) or thematic map of a prefecture or municipality.

For general use, the functionality of the J-RISQ earthquake report [15] was enhanced and made public in 2015 (URL: http://www.j-risq.bosai.go.jp/report/en/). For earthquakes where a seismic intensity of roughly three or above is measured, the seismic motion distribution, population exposure to the seismic intensity, past damaging earthquakes in nearby areas, and earthquake hazard information from J-SHIS are comprehensively, clearly, and efficiently summarized and provided using maps and tables. Namely, these five new functionalities were added to promote use at regional and individual levels, as well as international use (Fig. 4).

-Specification of region: A region (prefecture or municipality) can be selected and information can be magnified and viewed.

-KML download: Downloading in a GIS-compatible KML format is possible.

-Automatic update: The latest J-RISQ earthquake report is automatically displayed.

-RSS function: The latest information can be obtained using an RSS reader or RSS-compatible browser.

-Smartphone compatible: A smartphone-friendly dedicated page is available when accessed from a smartphone.

The 2016 Kumamoto earthquakes (M6.5 event and M7.3 event) with maximum seismic intensity of 7 caused great damage to human beings, buildings, and infrastructures. The seismicity is very active after M6.5 event occurred. We describe the estimations by the prototype real-time system for these earthquakes. The system distributed the first report 29 seconds after the M6.5 event occurred and a total of seven reports for about 10 minutes. The first report using data from 5 stations showed that population exposed to seismic intensity 6 lower or larger was 7,800. Finally the system estimated that population exposed to seismic intensity of 6 lower or larger was 620,000 and that of 6 higher or larger was 290,000 by using 1091 strong motion data. The estimated results of building damage showed that completely destroyed buildings were between 6,000 and 14,000 and partly destroyed were between 7,000 and 33,000. The distribution of estimated completely destroyed buildings spread 7 km long by 1 km wide in Mashiki town (Fig. 5).

For the M7.3 event occurred about 28 hours after the M6.5 event, the system distributed the first report 29 seconds after the M7.3 event occurred and a total of eight reports for about 11 minutes. Finally the system estimated that population exposed to seismic intensity of 6 lower or larger was 1,130,000 and that of 6 higher or larger was 670,000 by using 2391 strong motion data. The estimated results of building damage showed that completely destroyed buildings were between 16,000 and 38,000 and partly destroyed were between 18,000 and 88,000. The distribution of estimated completely destroyed buildings spread in Mashiki town similar to the result of the M6.5 event and Kumamoto city (Fig. 6). However, this result of damage building is out of consideration of the effect of the M6.5 event. At this time, we are not able to compare these results with real damage because the whole picture of real damage has not been grasped yet. A detailed analysis of real damage is to be desired.

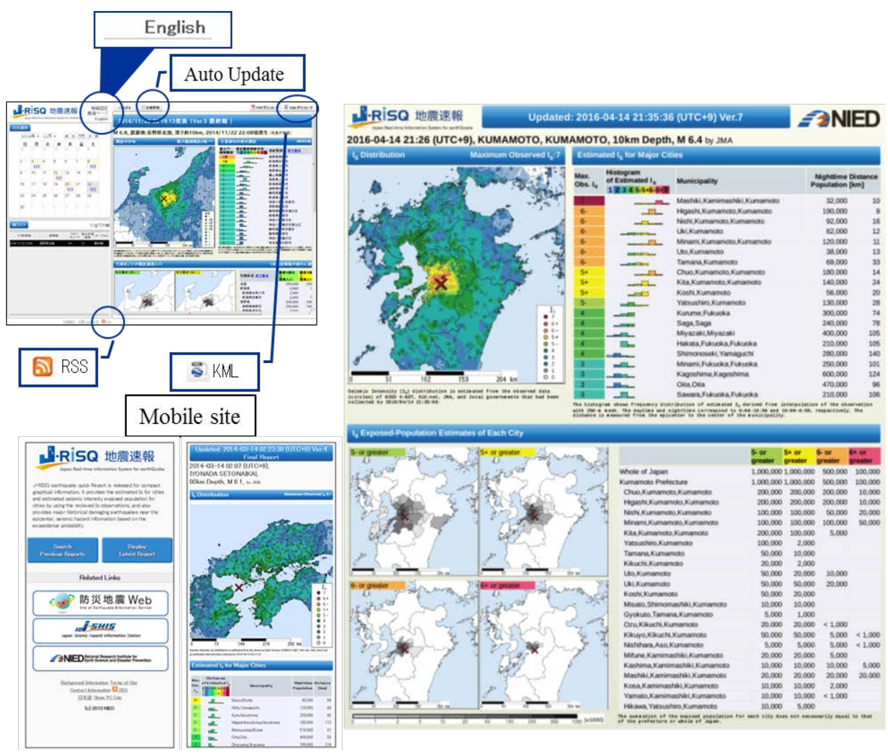

Fig. 4 Overview of new functionalities in J-RISQ earthquake report system

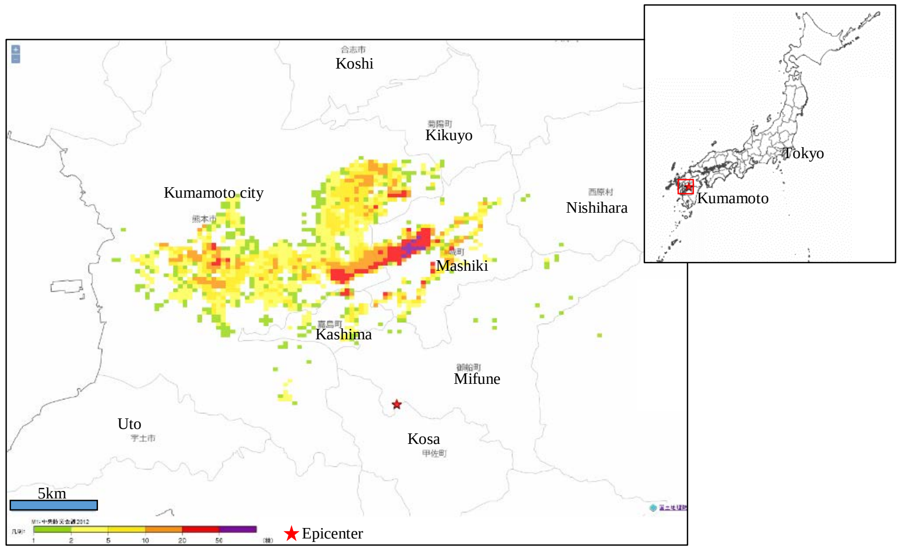

Fig. 5 Distribution of estimated completely destroyed buildings for M6.5 event by method 1 in Table 3

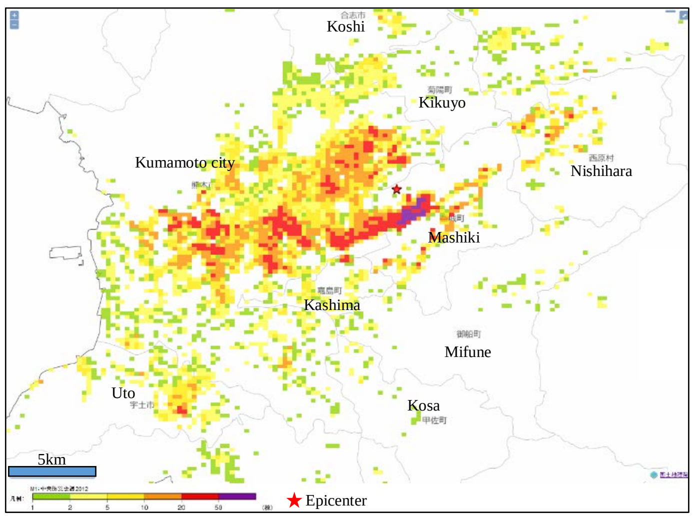

Fig. 6 Distribution of estimated completely destroyed buildings for M7.3 event by method 1 in Table 3

6. Summary

A building model covering all of Japan, an earthquake damage estimation and situation assessment method, and continuous strong motion measurement data are being integrated into the real-time earthquake damage information system. Estimated results such as the seismic motion, population exposure to a seismic intensity, and building damage distributions are provided in real time, as numerical data suitable for secondary use, to systems that support initial response decision making by local governments. Information on human damage is very important, in addition to building damage information, in supporting decision making about disaster response. Therefore, we intend to develop a population distribution model covering all of Japan that considers statistical population shifts based on the time of day. We will also develop and implement a human damage estimation method using building damage based on this model. Moreover, we plan to continue developing a real-time earthquake damage information system that covers the entire country of Japan.

7. Acknowledgements

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