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Paper:

Prototype of a Real-Time System for Earthquake Damage Estimation in Japan

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J-RISQ, a real-time system for earthquake damage estimation, was developed provide information by combining amplification characteristic data for subsurface ground accumulated in the course of the development of the Japan Seismic Hazard Information Station (J-SHIS), basic information on population and buildings, methods for predicting ground motion, methods for assessing building damage, and strong motion data observed by K-NET and KiK-net in real-time. J-RISQ estimates spatial ground motion distribution from seismic intensity information sent at different timing for observation stations, estimates population exposure to seismic intensity and building damage using estimated ground motion as input, and provides information to users via Web browser or email using Web GIS. J-RISQ estimation is based on intensity data obtained at different timing to ensure recency by updating results when it receives new data and updates results when it receives estimation results. J-RISQ provides and collects information using questionnaires from users on actual motion and damage situations. We have operated the system on trial from 2010 and estimated over 500 earthquakes in real-time. As a result, the system provides the first report 30 seconds after it receives intensity information at a certain level or larger, thus showing sufficient performance from the perspective of providing immediate information.

Keywords: J-RISQ, J-SHIS, K-NET, KiK-net, real-time

1. Introduction

It is extremely important to understand post-earthquake damage situations immediately when making decisions on establishing an appropriate initial response system. The Prompt Assessment of Global Earthquakes for Response (PAGER) used by the U.S. Geological Survey (USGS) is a system developed and operated for the purpose of understanding earthquake damage situations immediately in the world (Wald et al., 2008 [1]). The PAGER predicts ground motion distribution called a ShakeMap on the surface within 1 minute based on seismic information, i.e., at least earthquake location and magnitude, provided by the USGS National Earthquake Information Center (NEIC) within 20 minutes after an earthquake occurs. Human injury and economic damage are estimated by considering information on ShakeMap ground motion distribution and population and building distribution. Estimation results are expressed as probability distributions including uncertainties and appear on the Web as a "one PAGER" outline after warning levels are estimated on a scale of 4.

Based on emergency activities during the 1995 Great Hanshin-Awaji Earthquake, the importance has been pointed out of promptly understanding damage situations, integrating information in each step of preliminary, emergency, reconstruction and rehabilitation measures, and rapidly making comprehensive decisions. Against this background, the Japanese government Cabinet Office has organized and operated disaster information systems (DIS) using geographical information systems (GIS) that controls information on geography, ground characteristics, population, buildings, and disaster prevention facilities, and early estimation systems (EES) for seismic damage as a DIS subsystem (Cabinet Office, 2002 [2]). The EES for determining the approximate scale of an earthquake damage immediately after it occurs starts when information on seismic intensity of 4 or more is received online from the Japan Meteorological Agency (JMA) and estimates an overview of the number of destroyed buildings and resulting human injury within about 30 minutes after an earthquake occurs based on a database organized by municipalities nationwide in Japan regarding ground, buildings by structure and age and population by time period. As an example, earthquake damage in the 2000 western Tottori earthquake estimated by the EES was 8,000 destroyed buildings and 200 deaths, compared to actual figures for 400 buildings and 0 deaths. These significant differences suggest the many issues among difficulties in exposure distribution estimation for seismic hazard and damage estimation.

The Headquarters for Earthquake Research Promotion (HERP) released national seismic hazard maps for Japan comprised of different paired maps, i.e., a probabilistic seismic hazard map that combines long-term probabilistic analysis for earthquakes and strong motion analysis

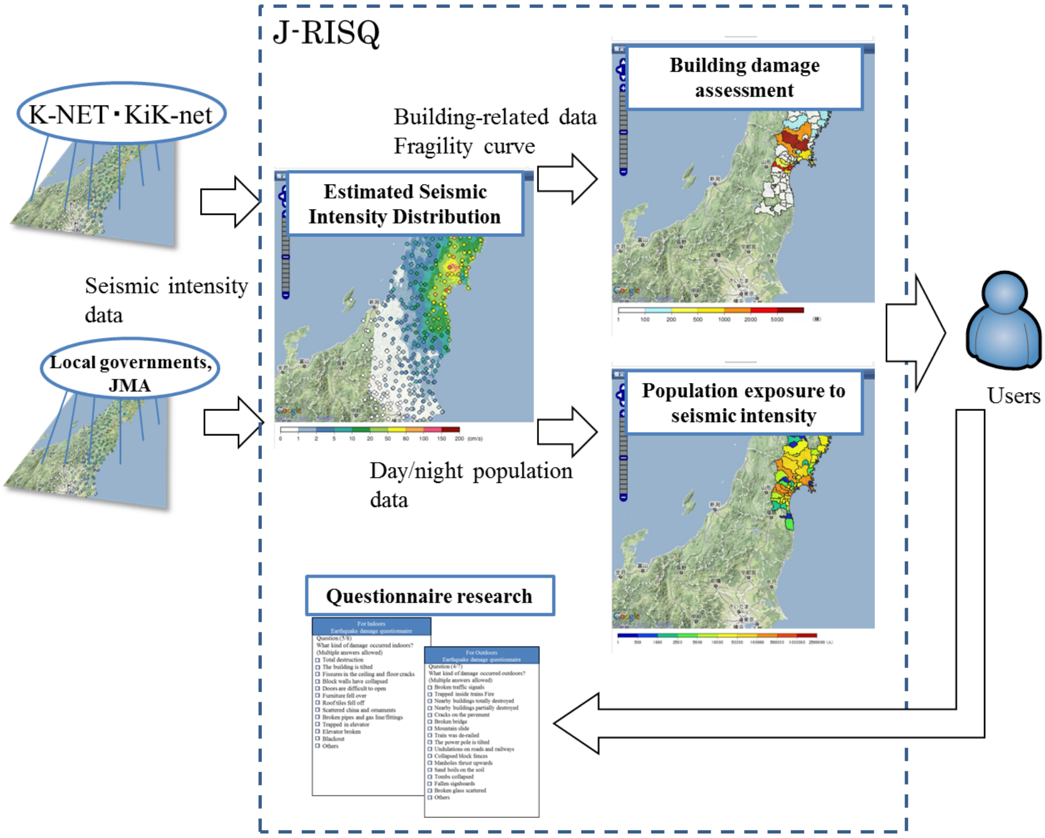


Fig. 1. Schematic diagram of J-RISQ.

and a seismic hazard map with specified source faults based on detailed strong motion analysis concerning an assumed scenario for a specific earthquake. The National Research Institute for Earth Science and Disaster Prevention (NIED) has published national seismic hazard maps on the Web and developed the Japan Seismic Hazard Information Station (J-SHIS) to provide data on prerequisite analysis process models for seismic activity, seismic sources, and subsurface structures (Fujiwara et al., 2009 [3]).

Since the 1995 Great Hanshin-Awaji Earthquake, strong motion observation systems in Japan were reconsidered. JMA, Fire and Disaster Management Agency, and NIED developed strong motion observation networks and seismic intensity observation networks spread densely and uniformly nationwide. K-NET and KiK-net developed and operated by NIED at 1,700 stations incorporate sufficient fundamental features as basic strong-motion seismography. And they can calculate various strong motion indexes such as the JMA seismic intensity, PGA, PGV, PGD, and real-time intensity, achieving quasireal-time data transmission (Kunugi et al., 2009 [4]). If a continuous communication line is available, the system performs real-time observation and data transmission. Real-time observation data at some stations are published on the Web as "Kyoshin Monitor" (Aoi et al., 2010 [5]).

As discussed above, a system for providing damage estimation information can presumably be developed and prove useful for appropriate decision-making on initial measures in 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 accumulated in J-SHIS development and observation data including real-time strong-motion data observed by K-NET and KiK-net. We have developed J-RISQ, a prototype real-time system for earthquake damage estimation, and are operating it experimentally. This paper descries an overview of J-RISQ and estimation status in actual earthquakes.

2. J-RISQ Overview

Figure 1 shows outlines of J-RISQ. The system consists of a receiver of seismic intensity data, a ground motion and damage estimator, an information display and distribution section, and a questionnaire information collection section. System features include the following:

- Seismic intensity is basically used for estimating damage.
- The system publishes distribution of ground motion, population exposure, and building damage on the Web estimated using Web GIS.
- Estimated information is accessible to those using PC browsers and is distributed to portable terminals of registered users. Users can see maps of estimation results on a Web site for portable device browsers.

- Questionnaire research about users is also conducted regarding actual motion and damage situations.

2.1. Seismic Intensity Data

The seismic intensity data receiver receives observed intensity data by K-NET, KiK-net, local governments, and JMA. Intensity data are sent at different timing sequentially from each station as ground motion spread, but not at the same time as an earthquake occurs. J-RISQ shifts to estimation mode when the number of observation points with an observed intensity of 2.5 or more exceeds a threshold value in a certain time range. This makes it possible to start estimation processing immediately after an earthquake occurs, which helps avoiding malfunction due to noise. Information promptness is also ensured by updating information. Estimation is performed based on seismic data at stations that are sent at different timing, and successive reports are issued. The first report is issued 30 seconds after the first seismic data is received and over 100 reports at most are updated in about 10 minutes.

2.2. Estimation of Ground Motion and Damage

In order to assess building damage and population exposure to seismic intensity, information on ground motion as input to assessment points is first required. In many cases, however, there are no observation stations that are very close to assessment points and have same ground characteristic as the assessment points. This means that ground motion over a wide area should be estimated based on observation information obtained at observation stations only. Among methods proposed for this purpose (Yamazaki et al., 1998 [6], Nojima et al., 2001 [7], Suetomi et al., 2007 [8]), this study estimates ground motion based on the following procedures: (1) converting intensity data observed on the surface to maximum velocity using an empirical formula, (2) estimating maximum velocity of engineering bedrock considering the ground amplification factor at each observation station, (1) estimating spacially-distributed maximum velocity of engineering bedrock by interpolation of data(2), and (2) determining distribution on the surface by multiplying data(1) by each amplification factor (AF).

Specifically, observed intensity is converted to maximum velocity on the surface using the following relational relationship between the seismic intensity (I) and peak ground velocity (PGV) (Fujimoto and Midorikawa, 2005 [9]).

$$I = 2.002 + 2.603 \log_{10} PGV - 0.213 (\log_{10} PGV)^2 \quad \ldots \quad (1)$$

Peak engineering bedrock velocity (PBV) is then determined by dividing obtained PGV by an AF. Note that the AF here is based on the average velocity of S waves up to a depth of 30 m from the surface (AVS30) identified from an engineering geomorphologic classification map (250-m mesh) that covers all of Japan (Wakamatsu and Matsuoka, 2008 [10]). The following equation of the empirical relationship between the AF and AVS30 formulated by Fujimoto and Midorikawa (2006) [12] is applied to the above AVS30:

$$\log_{10} AF = 2.367 - 0.852 \log_{10} AVS30 \quad \ldots \quad (2)$$

PBV obtained by the above processing is then spatially interpolated for 250-m meshes by means of interpolation implemented in GMT (Wessel and Smith, 1998 [13]) using the Delaunay triangle. PGV is next estimated by multiplying results by AF to calculate intensity distribution on the surface using Eq. (1). Because the number of 250-meshes covering the entire Japan is 6 million, J-RISQ accelerates processing by limiting the range of calculated meshes to a rectangular region including points with intensity data, i.e., 250-mesh data, by structure, i.e., wood/steel/reinforced concrete (RC) construction, and by the Building Standards Act (former/current) used for building data (60 million nationwide) in building damage prediction. Data for the number of buildings by age (Ooi et al., 2010 [5]) estimated using data for the number of buildings by structure estimated in units of third meshes nationwide and statistical data such as census statistics and the Housing and Land Survey are divided into 4 based on housing maps created based on nationally unified field research and fixed-property tax records published by municipalities. 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:

$$P(PGV) = \Phi\left(\frac{\ln PGV - \lambda}{\zeta}\right) \quad \ldots \quad (3)$$

$$P(I) = \Phi\left(\frac{I - \lambda}{\zeta}\right) \quad \ldots \quad (4)$$

$$\Phi(x) = 0.5\left(1 + erf\left(\frac{x}{\sqrt{2}}\right)\right) \quad \ldots \quad (5)$$

$P(PGV)$ is the damage rate with PGV as input, $P(I)$ the damage rate with a measured 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 research has proposed multiple fragility curves based on various data sets (i.e., Murao and Yamazaki, 2000 [16]). J-RISQ applies multiple fragility curves to each structure type as shown in **Table 1**; estimation methods are selected from 4 patterns on trial by combining curves. 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:

$$N_{m,k} = \sum_i \sum_j P_{m,i,j,k} T_{m,i,j} \quad \ldots \quad (6)$$

where m is the mesh number, k the damage level, i the type of building, j the observed Building Standard Act, N

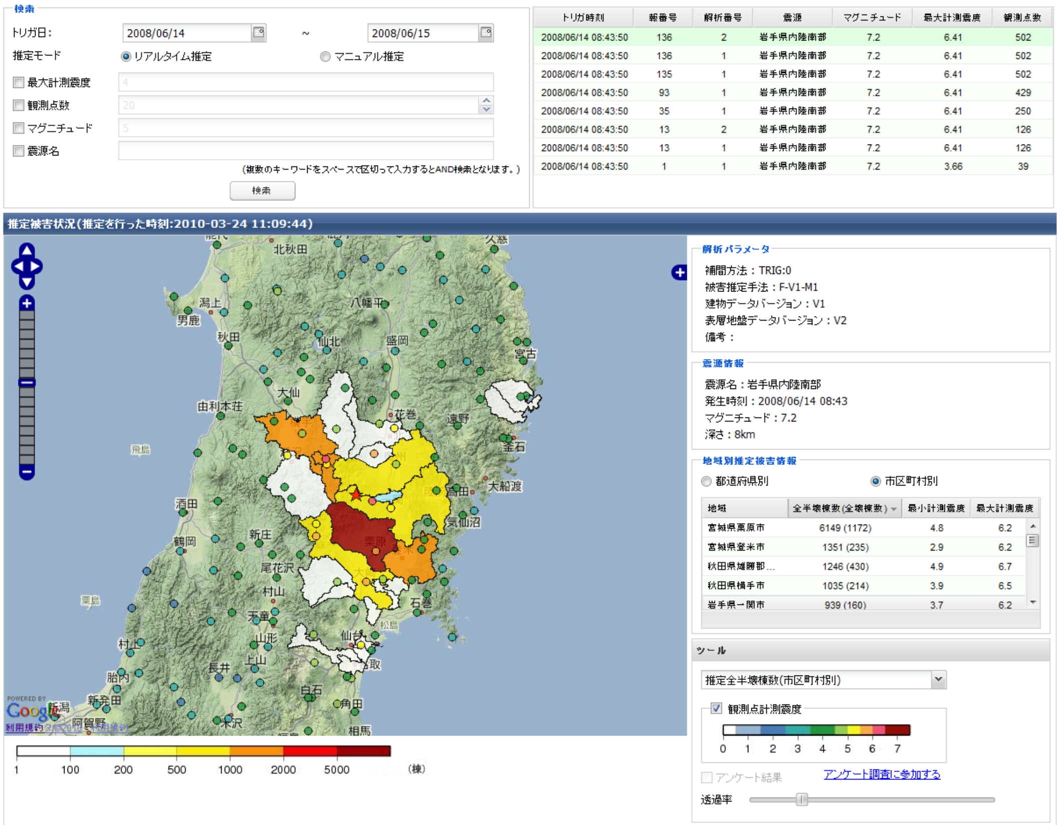


Fig. 2. Example of estimation results displayed on a Web browser.

Table 1. Building damage estimation methods available in J-RISQ.

Method	Structure	Reference
method1	Wooden	Horie (2004) [17]
	Reinforced-Concrete	Murao and Yamazaki (2000) [16]
	Steel	Murao and Yamazaki(2000) [16]
method2	Wooden	Horie (2004) [17]
	Reinforced-Concrete	Murao and Yamazaki (2002) [18]
	Steel	Murao and Yamazaki (2002) [18]
method3	Wooden	Murao and Yamazaki (2002) [18]
	Reinforced-Concrete	Murao and Yamazaki (2002) [18]
	Steel	Murao and Yamazaki (2002) [18]
method4	Wooden	Cabinet Office (2004) [19]
	Reinforced-Concrete	Cabinet Office (2004) [19]
	Steel	Cabinet Office (2004) [19]

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:

$$R_{m,k} = N_{m,k} / \sum_i \sum_j T_{m,i,j} \quad \cdots\cdots\cdots\cdots \quad (7)$$

Day or night population data are used depending on the time an earthquake occurs. Day population data is based on the 2005 and 2006 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.

2.3. Information Display and Distribution

The information display and distribution section visualizes and externally distributes estimation results. Visualization of damage estimation results is constructed using Web GIS and results are applied to common maps available on the Internet. **Fig. 2** shows an example of displayed results. Users retrieve estimation results with keywords of seismic source information such as seismic location name and magnitude, in addition to time period, observed maximum intensity, or the number of observation points. Retrieval results are displayed in a list and maps of 250-m mesh, prefecture, or municipality depending on selected results. A list of numerical data for estimation results by prefecture and municipality (building damage and population exposure to seismic intensity) is provided along with earthquake information and analysis conditions.

Information is distributed outside the system to email addresses of registered users. Users register a desired distribution area selected from among nationwide, prefectures, and municipalities and distribution level with a threshold value of maximum intensity in advance. When registered conditions are satisfied, information on estimated building damage in a registered area, i.e., the number of buildings destroyed completely and partly, and on estimated population exposure to seismic intensity is dis-

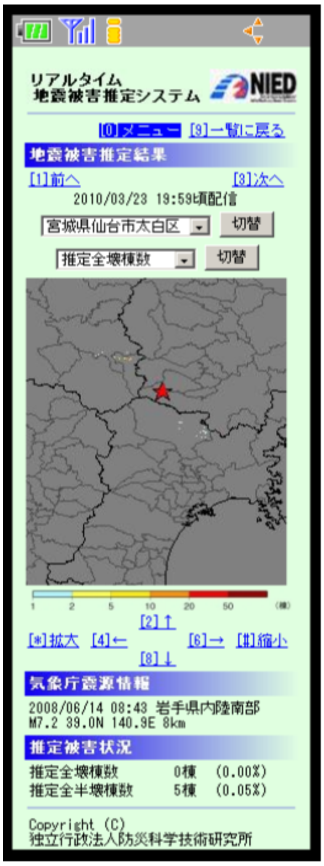


Fig. 3. Example of estimation results displayed on a portable terminal.

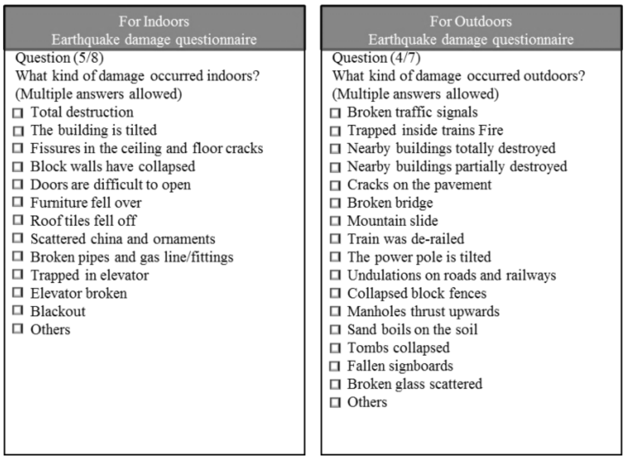
tributed via email. Users access to a Web system for portable terminals using the link in distributed email text and browse damage distribution maps as shown in **Fig. 3**. The Web system for portable terminals provides maps associated with past distribution history in addition to real-time estimated damage maps.

2.4. Questionnaire Information Collection

Fragility curves used in J-RISQ are developed using limited seismic damage examples as basic data. Since the damage rate tends to increase rapidly at a certain ground motion level, a slight difference at a level at which damage begins being caused may significantly affect building damage estimation. Because the structure type, age, and fragility curve are assigned to building data used in the system based on certain assumptions, estimation results may include errors depending on the earthquake occurrence situation. In order to increase the accuracy of real-time seismic damage estimation in the future, certain important issues must be considered, i.e., increasing data for ground amplification, buildings, population as a basis for estimation and improving estimation methods.

It is also important to process estimation incorporating actual damage information by effectively collecting information on actual ground motion and damage and feeding it back to the system. USGS PAGER uses a questionnaire system called “Did you feel it?” (DYFI) for ground motion and damage from Internet users in order to increase ShakeMap prediction precision (Wald et al., 1999 [20]). Questionnaire websites of DYFI for each earthquake covered by PAGER have been established and respondents fill out questionnaires after inputting the country in which they live and their postal (zip) codes. Questionnaires include about 20 questions on motion intensity, duration time, response of respondents, damage of buildings, etc.

J-RISQ sets up a questionnaire website automatically with the aim of collecting information on motion level and damage for a certain period after an earthquake. Location information is important when collecting the above information and obtained addresses and postal (zip) code input by users or GPS positioning information from portable information terminals. Questions differ depending on location conditions of respondents, e.g., outdoors or indoors, and a total of 10 multiple-choice questions are asked as shown in the example in **Fig. 4**.



For Indoors
Earthquake damage questionnaire
Question (5/8)
What kind of damage occurred indoors?
(Multiple answers allowed)
- ☐ Total destruction
- ☐ The building is tilted
- ☐ Fissures in the ceiling and floor cracks
- ☐ Block walls have collapsed
- ☐ Doors are difficult to open
- ☐ Furniture fell over
- ☐ Roof tiles fell off
- ☐ Scattered china and ornaments
- ☐ Broken pipes and gas line/fittings
- ☐ Trapped in elevator
- ☐ Elevator broken
- ☐ Blackout
- ☐ Others

For Outdoors
Earthquake damage questionnaire
Question (4/7)
What kind of damage occurred outdoors?
(Multiple answers allowed)
- ☐ Broken traffic signals
- ☐ Trapped inside trains Fire
- ☐ Nearby buildings totally destroyed
- ☐ Nearby buildings partially destroyed
- ☐ Cracks on the pavement
- ☐ Broken bridge
- ☐ Mountain slide
- ☐ Train was de-railed
- ☐ The power pole is tilted
- ☐ Undulations on roads and railways
- ☐ Collapsed block fences
- ☐ Manholes thrust upwards
- ☐ Sand boils on the soil
- ☐ Tombs collapsed
- ☐ Fallen signboards
- ☐ Broken glass scattered
- ☐ Others

Fig. 4. Example of questionnaire (indoors on the left, outdoors on the right).

3. J-RISQ Estimation

The operating status of J-RISQ during actual earthquakes is described in the sections. The system was operated in trials in 2010 and had estimated information on over 500 earthquakes as of April 2013. **Fig. 5** shows a histogram of elapsed time from reception of intensity information at K-NET or KiK-net stations to the first report email distribution to portable information terminals. The graph shows data for all estimated earthquakes (513) and those with observed maximum intensity exceeding 5 lower (58). Both types of data are distributed and show peaks at 20-30 seconds. In 78% of all estimated earthquakes, the first report was issued within 1 minute, while in 67% of earthquakes with an observed maximum intensity exceeding 5 lower, the first report was issued within 30 minutes, showing sufficient immediacy for information provision immediately after an earthquake.

Regarding the estimation status for individual earthquakes, the largest earthquake during the trial operating

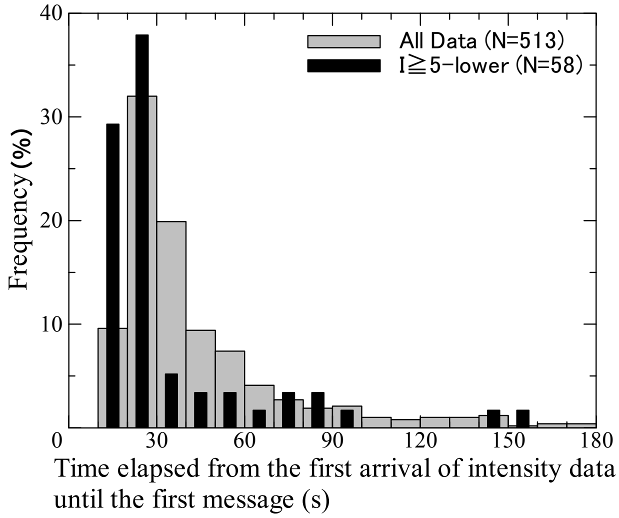


Fig. 5. Histograms of operating time until the first report. Data for all earthquakes are in gray and that for earthquakes with an observed maximum intensity of 5 lower or larger are in black.

period was the 2011 Tohoku-Oki earthquake (Mw9.0). The NIED operating J-RISQ (Tsukuba City, Ibaraki Prefecture) suffered motion with an intensity of 6 lower and could not provide sufficient estimation because the data center function for strong-motion observation networks did not work due to blackouts and other reasons (Kunugi et al., 2012 [21]).

The largest earthquake after the system was restarted after the 2011 Tohoku-Oki earthquake occurred on April 7, 2011, offshore Miyagi Prefecture (M_{JMA}7.1 with a maximum intensity of 6 upper). **Figs. 6** and **7** show reports of seismic intensity distribution for this earthquake and estimation results of population exposure to a seismic intensity of 5 lower or larger by municipality. J-RISQ distributed the first report using data from 8 stations 31 seconds after the earthquake occurred (**Figs. 6(a)** and **7(a)**). Observation stations increased as seismic wave propagated and the second (18th internal processing) report was distributed using data from 151 stations 1 minute 9 seconds after the earthquake (**Figs. 6(b)** and **7(c)**), the third (40th) using data from 539 stations 5 minutes 36 seconds after the earthquake (**Figs. 6(c)** and **7(c)**), and the final report (63rd) using data from 2,352 stations 19 minutes 39 seconds after the earthquake (**Figs. 6(d)** and **7(d)**). Estimation results showed that population exposed that night to a seismic intensity of 5 lower or larger was 4.4 million and that of 6 lower or larger was 1.2 million. Although changes in building data after the 2011 Tohoku-Oki earthquake were not considered, based on the building damage estimation results using method 1 (**Table 1**) for M_{JMA}7.1, 6,000 buildings were completely destroyed and 16,000 buildings partly destroyed. Actual damage after the 2011 Tohoku-Oki earthquake has been reported in detail by the Fire and Disaster Management Agency (Fire and Disaster Management Agency, 2013 [22]). That report contains damage due both to aftershocks generated

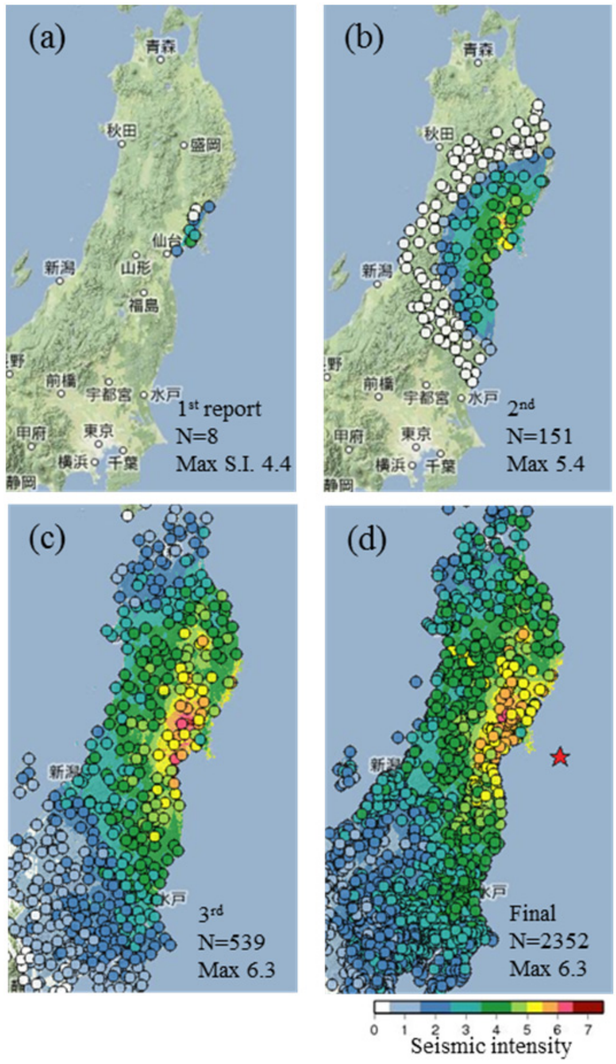


Fig. 6. Estimation results for seismic intensity during the earthquake off Miyagi Prefecture on April 7, 2011. (Circles indicate observed seismic intensity).

after March 11, 2011, and that indistinguishable from earthquakes out the aftershock zone. This means that April 7, 2011, earthquake results cannot be compared separately to J-RISQ estimation results. A detailed analysis of damage is to be desired, however.

4. Conclusions

A prototype system for real-time seismic damage estimation system has been developed that immediately estimates damage and provides estimated results by combining amplification characteristic data for subsurface ground accumulated in the course of the development of J-SHIS, basic information on population and buildings, methods for predicting ground motion, damage assessment methods for buildings, and observation data such as real-time strong motion data obtained by K-NET and KiK-net. Basically, the system does not use seismic source information, but estimates ground motion distribu-

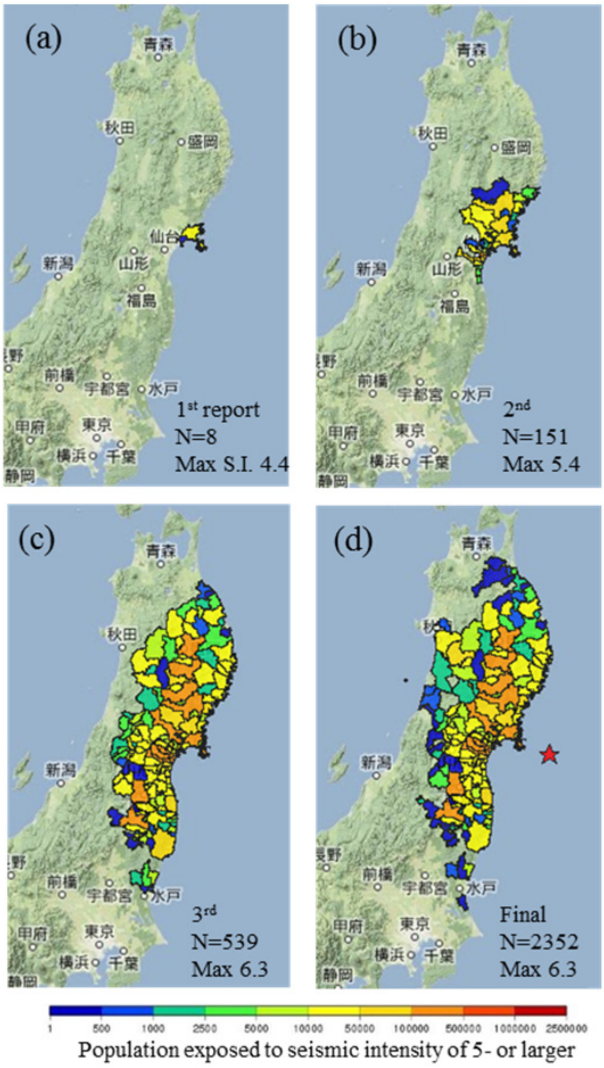


Fig. 7. Estimation results for population exposure to seismic intensity of 5 lower or larger by municipality during the earthquake off Miyagi Prefecture on April 7, 2011.

tion on the surface from observed intensity, estimates population exposure to seismic intensity and building damage using estimated ground motion as input, and provides information to users via a Web browser or email using Web GIS. The system performs estimation based on intensity data obtained at different timing to ensure immediacy by updating estimation results it receives new data and updates estimation results when it receives new results. While providing such information, and it collects information by conducting questionnaires regarding actual motion and damage situation to users. We have operated the system on trial from 2010 and estimated over 500 earthquakes in real-time. As a result, the system provides the first report 30 seconds after it receives intensity information at a certain level or more, showing sufficient performance from the perspective of immediate information provision. Estimation results should be reviewed and population and building data should be improved as a basis for damage estimation in the future. The system is still in the prototype stage, so actual processing results have not been released to the general public and information collection by questionnaire has not performed. Through experiments as those performed by Nakamura et al. (2013) [23], the effectiveness of needs and information from questionnaires regarding macroscopic damage estimation information immediately after an earthquake should be investigated and the methods reflecting information from users obtained in questionnaire to estimation results are needed. J-RISQ adopts seismic intensity as a basic index that is calculated by K-NET, KiK-net, municipalities, and JMA. Because indices highly associated with building damage are proposed (i.e., Sakai et al., 2002 [24]), it is important to compare and investigate these indices as appropriate for real-time estimation. In order to utilize a wide range of information in the course of using the system practically, information provision for interoperation using global standards such as the Web Map Service (WMS) and Web Feature Service (WFS) is needed.

Acknowledgements

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