Paper:

Development and Testing of a Mobile Application for Recording and Analyzing Seismic Data

Shohei Naito*, Hiroki Azuma*, Shigeki Senna*, Mutsuhiro Yoshizawa, Hiromitsu Nakamura*, Ken Xiansheng Hao*, Hiroyuki Fujiwara*, Yoshiharu Hirayama***, Noboru Yuki***, and Minoru Yoshida*****

*National Research Institute for Earth Science and Disaster Prevention
3-1 Tennodai, Tsukuba, Ibaraki 305-0006, Japan
E-mail: {naito, azzie, senna, manta, hao, fujiwara}@bosai.go.jp
*Takenaka Corporation
Otsuka1-5-1, Inzai, Chiba 270-1395, Japan
E-mail: yoshizawa.mutsuhiro@takenaka.co.jp
***Hakusan Corporation
J Tower, 1-1 Nikko-cho, Fuchu-shi, Tokyo 183-0044, Japan
E-mail: {hirayama, yuki, yoshida}@hakusan.co.jp
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i-jishin, an app that measures earthquakes using MEMS acceleration sensors built in mobile information terminals such as smartphones and geonavi that receives, stores, and displays seismic records on a cloud server is developed. The test results for the performance validation of the system, an example of the application to strong-motion observation of buildings, and approach of field test for local communities are introduced.

Keywords: mobile terminal, MEMS, cloud, sensor network, On-Site experiment

1. Introduction

Records of the destructive strong motions occurring close to seismic sources are essential information for the aseismic design of structures and development of damage reduction technologies, in addition to the clarification of strongmotion occurrence. For this purpose, construction of an observation network for strong motions with high density is indispensable.

Two strong-motion seismograph networks have been developed in Japan: K-NET consists of more than 1,000 observation stations distributed every 20 km uniformly covering Japan; KiK-net consists of pairs of seismographs installed in boreholes together with highsensitivity seismographs (Hi-net) installed on the ground surface, deployed at approximately 694 points (as of April 1, 2008). Along with the data obtained using these seismograph networks, the seismic data measured at a total of approximately 4,239 points (as of April 1, 2008) are integrated by the Japan Meteorology Agency (JMA), including those obtained at the observation points of the JMA and seismic information network developed by the Japanese Fire and Disaster Management Agency in each prefecture. Such information is announced to the public via TV and the like immediately after an earthquake occurs [1]. In addition, municipalities, universities, and independent administrative agencies have been operating strong-motion seismographs.

However, while strong-motion observation facilities have been developed more widely in Japan than in other countries, neither the strong-motion observation of buildings is performed well nor are the responses of each building sufficiently recognized during earthquakes, with some individual data acquisition by universities, independent administrative agencies, and private companies.

The reasons considered for not performing the strong-motion observation of buildings widely are that the observation instruments are expensive, special techniques are required for setup and data acquisition, and people are concerned about harmful rumors because of information disclosure when a building is determined to be vulnerable to earthquakes.

Meanwhile, along with the recent progress in information-communication technologies, acceleration sensors such as Micro Electro Mechanical Systems (MEMS) using semiconductor integrated circuits are widely used for electronic equipment control and game controllers. Literature [2] shows an example in which MEMS acceleration sensors are used for strong-motion observation. These sensors have the advantage of being manufactured in a smaller size at a lower cost when compared with the conventional ones, whereas because they comprise self-noises ranging from 10 gal or less to several 10 gal, individual sensors should be appropriately selected [3].

The following are examples of developing low-cost seismometers using MEMS acceleration sensors: a small seismometer, which transmits the measured intensity and

Spectrum Intensity (SI) values via Local Area Network (LAN) in real time [4]; an alarm device, which coordinates the on-site earthquake information measured using a built-in MEMS acceleration sensor with the Earthquake Early Warning [5]; and a network-type seismometer with a noise level of approximately ± 0.1 gal using a Giant Magneto Resistive (GMR) sensor, which is used for hard disk readers [6]. Literature [7] shows an example of field tests for very dense seismic array observations using a network-type seismometer.

Moreover, various trials have been performed in order to share the seismic observation records obtained by the MEMS acceleration sensors. Examples include development of a system for publishing the seismic information on the Internet along with a notification of the Earthquake Early Warning (EEW) using MEMS sensors connected to the PCs that are provided to ordinary households [8], construction of a seismic sensor network worldwide by publishing the data on the Internet by connecting various sensors with different accuracies to PCs [9], and development of a seismic observation system using PCs with inbuilt MEMS sensors [10, 11].

It is observed that the most widely used terminals incorporating MEMS acceleration sensors are mobile information terminals such as smartphones, tablet computers, and mobile music players. These terminals are equipped with MEMS acceleration sensors for screen operation and incorporate wireless communication function by means of Wi-Fi and also have a battery. Literature [12] has evaluated the seismic observation performance using MEMS acceleration sensors incorporated in such mobile information terminals.

This study discusses the development of an app i-jishin, for measuring earthquakes using MEMS acceleration sensors incorporated in mobile information terminals and a server, geonavi, which aggregates the data obtained using terminals with the app installed and is implemented in cloud environments providing information on the seismic waveforms and the corresponding seismic intensity values to the users on the Web.

In addition, the accuracy of the observation records obtained using these systems is validated, and the examples of application to strong-motion observation of buildings and field tests for local deployment are described.

The densest observation network ever formed by general users with no special knowledge about seismic measurement is considered to be constructed experimentally by using widespread MEMS acceleration sensors for seismic observation. When the observation points are increased, an effect by the building or ground while obtaining the local seismic records, depending on the installation environments, is also expected. Furthermore, the purpose of this approach is to realize a society resistant to disasters by raising awareness about disaster reduction and promoting earthquake-resistant structures through experiments sharing information on motions during earthquakes.

2. Development

2.1. i-jishin

i-jishin was released as an app exclusive for iOS terminals in August 2010. By installing the i-jishin app in any terminal of an iPhone, iPad, or iPod touch for measurement, the acceleration records of each component of NS, EW, and UD at a sampling rate of 100 Hz obtained using MEMS acceleration sensors incorporated in a terminal are stored in a built-in memory of the terminal main body. However, the sampling rates of such MEMS sensors fluctuate; therefore, the measurement data are corrected at 100 Hz on the basis of the correct time obtained by an external Network Time Protocol (NTP) server while the actual sampling interval is at approximately 98 Hz at the maximum. This sampling data creation process at 100 Hz is conducted by the i-jishin app installed in a terminal. It is noted that the number of channels and sampling frequency cannot be changed. The resolution of the measurement data with devices such as iPhone4, iPad, and iPod touch is approximately 12 bit (1.6 gal).

Either or both of the following two methods are selected as the trigger methods: level trigger, which is determined when the acceleration exceeds the predetermined threshold values; external trigger, which transmits the trigger signals to an i-jishin terminal within a distance of 500 km from an epicenter when a geonavi server receives an Earthquake Early Warning. The trigger data recorded in the memories built in a terminal are immediately uploaded via Wi-Fi or the 3G line by means of File Transfer Protocol (FTP). However, when Wi-Fi and the 3G line are off-line, the FTP communication enters the stand-by mode and transmits the recorded data from the oldest one at a time when Wi-Fi or the 3G line turns on-line. The upper limit of the number of files of data to be stored in memories built in a terminal is 30 for 5 min at the maximum per file. When the upper limit is exceeded, the oldest files are deleted.

The waveform, corresponding values of the measured intensity, and progress status of the data upload are indicated on a liquid crystal display of the iOS terminal in the middle of the observation. The system has a simple analysis function to display the spectrum of the recorded data on a terminal and a display function to indicate the corresponding values of the measured intensity on maps.

2.2. Geonavi

Geonavi, a server system, is implemented in a virtual server in cloud environments as shown in **Fig. 1**, and it manages the received measurement data and Earthquake Early Warning. The seismic waveform data are accessible by general users on the website of geonavi.[1] Users can download the obtained waveforms and corresponding values of the measured intensity from the maps on the Web.

The measurement data are associated with the corresponding telegraph message of the JMA for Earthquake

1. http://www.geonavi.com/

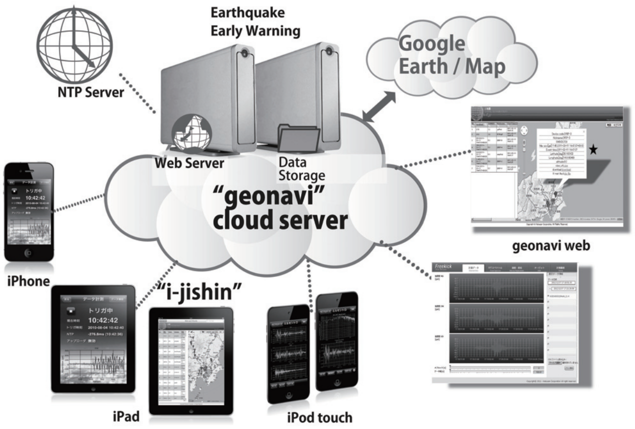

Fig. 1. Key map of "i-jishin" and "geonavi."

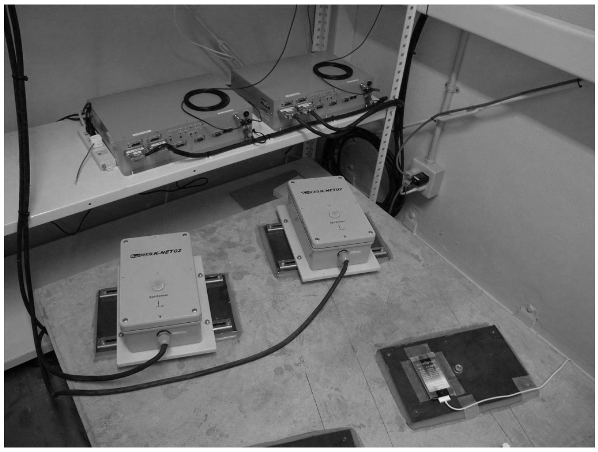

Fig. 2. Earthquake observation test of "i-jishin" and K-NET02.

Early Warning (the final issue) for advanced users, and the users can obtain the desired seismic records by sorting the data by conditions such as earthquake occurrence time, magnitude, and maximum intensity. The seismic records use the CSV format. The system can transfer the data into the K-NET ASCII format, which adds the seismic source information, but currently unpublicized. Simple analyses including waveform creation, integration, FFT, and locus display on browsers.

Data download, data sorting by Earthquake Early Warning, and analyses on browsers as discussed above are performed on a cloud server.

3. Performance Tests

3.1. Earthquake Observation

For validating the performance of the i-jishin terminal as a seismometer, an iPod touch was fixed to a seismometer pier of the observation facility at National Research Institute for Earthquake Science and Disaster Prevention (3-1 Tennodai, Tsukuba City, Ibaraki Pref.), as shown in **Fig. 2**, and parallel observation tests with a K-NET02 strong-motion meter have been performed since February 2011. Here, the time of the iPod touch was synchronized to the NTP whereas that of the K-NET02 strong-motion meter was synchronized to the GPS.

The 2011 off the Pacific coast of Tohoku Earthquake occurred on March 11 during the observation, with records of the main shock and multiple aftershocks as shown in **Fig. 3**.

When comparing the corresponding values of the measured seismic intensity on the Japanese scale calculated on the basis of the i-jishin and K-NET02 seismometer records, the value of the measured seismic intensity in the cases are 2.5 or more with differences within ±0.1, as shown in **Fig. 4**.

However, noise components of approximately ±5 gal are continuously mixed with the data owing to self-noise of the MEMS sensors, even when there is no earthquake. The accurate waveform data on earthquakes with an seismic intensity of 2 or less are therefore hidden by the noises, as shown in **Fig. 5**.

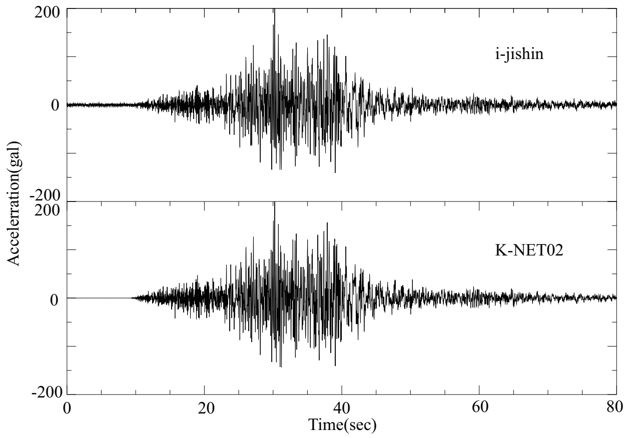

Fig. 3. Comparison of the waveforms recorded by "i-jishin" and K-NET02 (seismic intensity is 4.7, recorded at 17:16 2011/04/11).

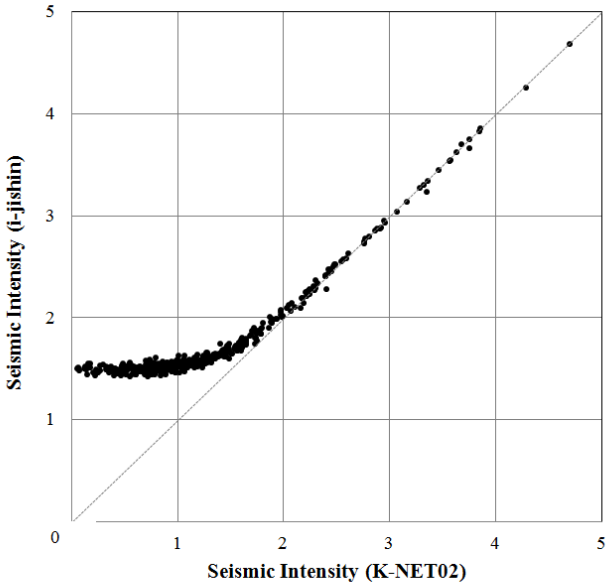

Fig. 4. Relationship between the seismic intensities recorded by "i-jishin" and K-NET02.

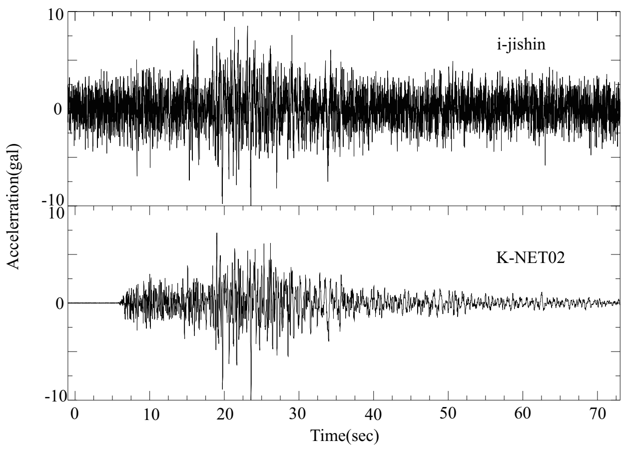

Fig. 5. Comparison of the waveforms recorded by "i-jishin" and K-NET02 (seismic intensity is 2.3, recorded at 17:01 2011/03/18).

3.2. Vibration Tests on the Shaking Table

For the purpose of more detailed performance verification, vibration tests are conducted by fixing the i-jishin terminals (iPod touch, iPhone4, and iPad) and a measurement standard (JA-40GA08 manufactured by Japan Aviation Electronics Industry, Ltd.) to a shaking table, as shown in **Fig. 6**, and excited at 0.5-10 Hz and 5-1500 gal for 2 min with 32 combinations of sine waves as summarized in **Table 1**, for each component of NS, EW, and UD. The time of each terminal was synchronized to that of the NTP.

In the 32 predetermined shaking experiments, all the i-jishin terminals achieved data acquisition of waveforms with maximum amplitude and frequency equivalent to those obtained using the standard. Here, the maximum recorded values are approximately $+1{,}000$ gal when shaken at 1,500 gal in the UD direction. This is because of the fact that an offset of gravity acceleration occurs in the UD direction while the full scale of the MEMS sensors used for the i-jishin terminals is $\pm 2{,}000$ gal. In addition, particularly when shaken at a maximum acceleration of 20 gal or less, the records of i-jishin and the standard differed significantly owing to noises.

The calculation results of the corresponding values of the measured seismic intensity on the Japanese scale based on i-jishin and the standard records show differences within ± 0.1, as shown in **Fig. 7**. These results demonstrate that the performance of i-jishin is effective to calculate the corresponding values of the measured seismic intensity in the current shaking tests with a minimum input of the calculated intensity of approximately 2.5.

Moreover, when comparing the spectrum data of the i-jishin terminals and the standard, noises considerably affected the i-jishin terminals, particularly in the case of shaking at a frequency of 3 Hz or more. In addition, multiple peaks are shown in the records of the standard (**Fig. 8**). This is because of the aliasing effect of noises at more than the Nyquist frequency (50 Hz) because anti-aliasing filters were not used. The cutoff frequency of the low-pass filter of the MEMS sensors used in the i-jishin terminals is 74 Hz.

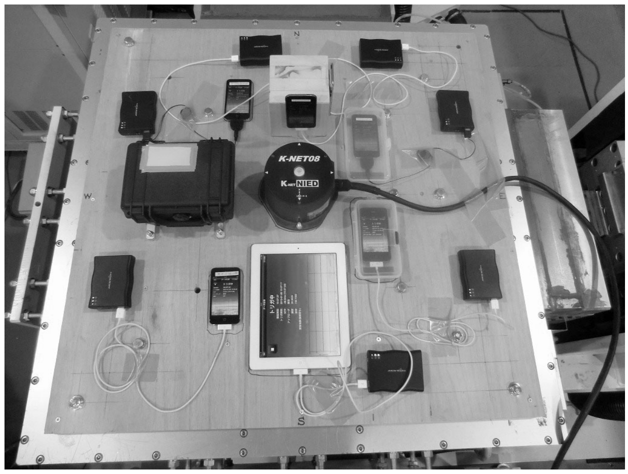

Fig. 6. Vibration test of "i-jishin" and JA-40GA08.

Table 1. Shaking schedule.

Frequency	Acceleration (gal)								
(Hz)	5	10	20	40	100	150	500	1000	1500
0.5	○	○	○	○					
1	○	○	○	○	○	○			
3		○	○	○	○	○	○		
6		○	○	○	○	○	○	○	○
10		○	○	○	○	○	○	○	○

3.3. Vibration Tests in E-Defense

The authors participated in the experiments [13] conducted in E-Defense, a 3-D full-scale earthquake testing facility (Miki City, Hyogo Pref), in October 2011, with the objective of field testing for earthquake observation in buildings using i-jishin terminals. The experiments were performed in the course of a special project for earthquake disaster mitigation in Tokyo metropolitan area, [II] studies on evaluating the aseismic performances and ensuring functions of urban facilities, (2) research and development of damage reduction measures for long-period ground motions. Twelve iPod touches with i-jishin installed were set in a test body simulating motions of a full-scale reinforced high-rise building corresponding to 27 stories to obtain records of 10 types of seismic waves and white noise waves. Terminals were stabilized in three different manners on floors, walls, and desktop, by assuming actual usage using two-sided adhesive tape on the metal, as shown in **Fig. 9**. The external batteries supplied power to the terminals, and the time was corrected by referring to an NTP server via wireless LAN.

As a result of the experiments conducted for 3 days, the data of all the input waves exceeding the trigger level (50 gal) predetermined for the i-jishin terminals were obtained. The noise levels were higher than those recorded by servo accelerometers (TA-25E manufactured by Tokyo Keiki Inc.) placed on the same floors of the test body, while the equivalent maximum amplitude and dominant frequency were obtained. The Fourier spectrum ratio of the i-jishin terminals and TA-25E placed on a shaking bed correlated well at a frequency band of approximately 0.1-

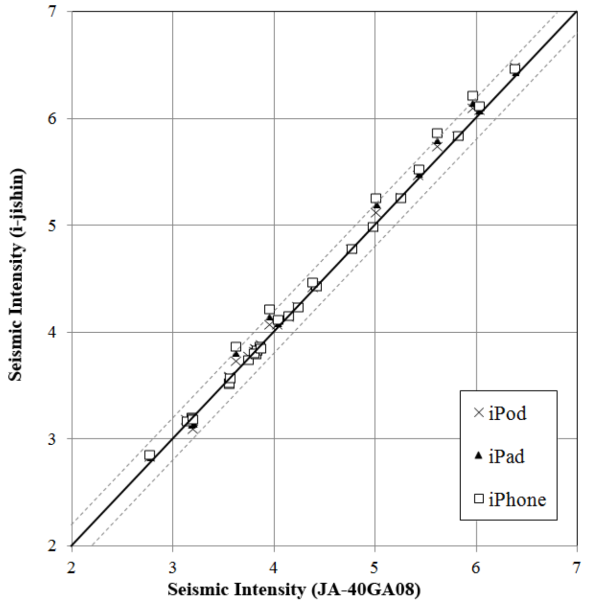

Fig. 7. Relationship between the seismic intensities recorded by "i-jishin" and JA-40GA08 (EW component).

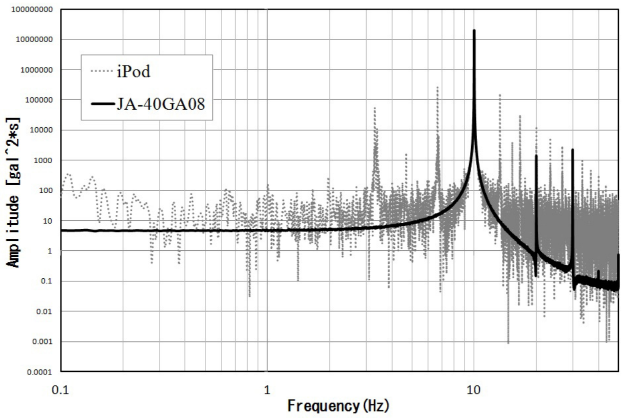

Fig. 8. Comparison of the spectra recorded by "i-jishin" and JA-40GA08 (1500 gal, 10 Hz, EW component).

5 Hz, as shown in **Fig. 10**.

The calculation results of the velocity response spectrum based on the i-jishin terminals placed on the top floor of the test body indicated a long-period eigen frequency for the test body, depending on the intensity of the input seismic waves, as shown in **Fig. 11**, demonstrating nonlinear behaviors of the test body when strong motions occur.

Differences were observed in the records obtained at different locations on the same floor, and **Fig. 12** shows the records including the responses of the desks and walls on which i-jishin terminals were placed. In the case of the response of the walls, pulsed waveforms were confirmed, which were generated when nearby furniture and fixture moved and fell down hitting the walls. When the system is actually used for motion observation of buildings, the terminals should be stably fixed to the floors or structure walls by selecting the locations at which the nearby furniture is less likely to move or fall down because of motions and ensuring the constant power supply and wireless communication in the environments.

Fig. 9. Installation of "i-jishin."

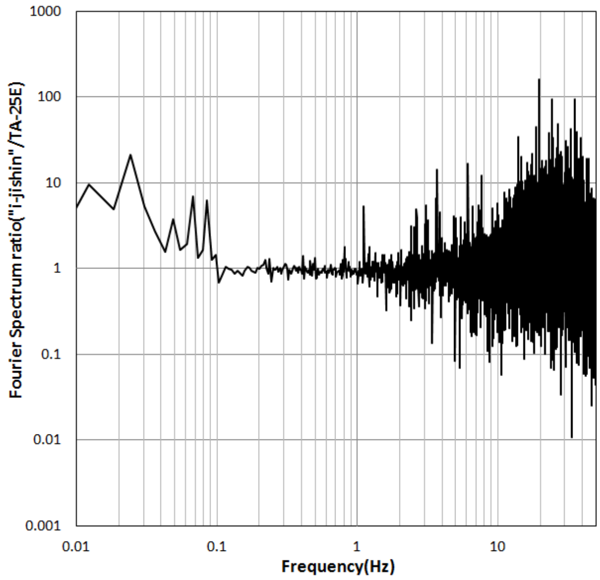

Fig. 10. Fourier spectrum ratio of "i-jishin" to TA-25E.

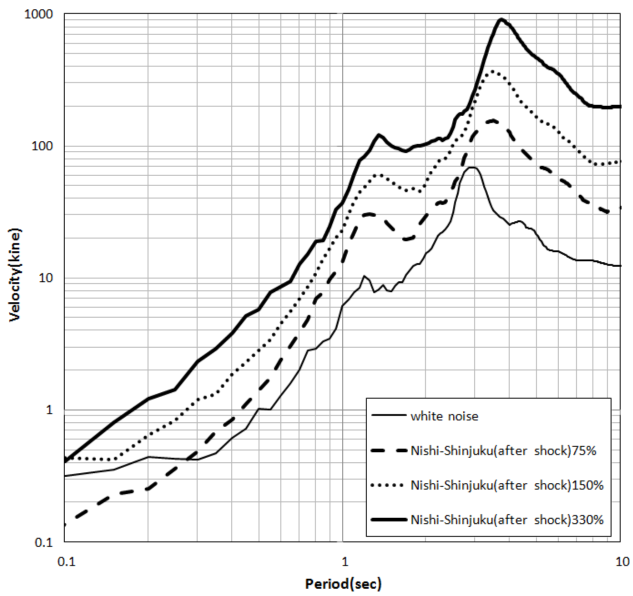

Fig. 11. Velocity response spectrum calculated from "i-jishin" data observed at the top floor.

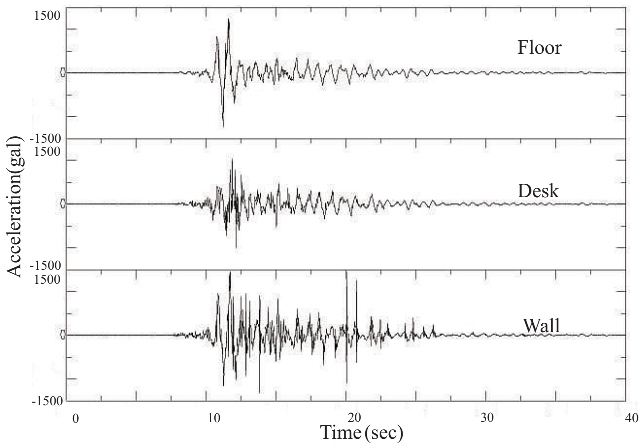

Fig. 12. Comparison of the waveforms recorded by "i-jishin" installed in different places in the same floor (JMA-Kobe 75%).

4. On-Site Experiments

The above performance test results confirm that the system can be used for observation of earthquakes with an seismic intensity of 3 or more, which are relatively less affected by noises by installing the i-jishin app to the iOS terminals and satisfying the conditions of fixture method, power supply, and wireless communication.

The use of small terminals such as iPod touch enables easy fixture of the main body onto the smooth floor surface within a minimal space, without using complicated wiring. In addition, because the system uses mobile information terminals of affordable prices for general users in the Wi-Fi communication environments such as home and office, it familiarizes seismic observation conventionally by experts and rapidly increases the penetration rate of the seismographs.

With the above effects in mind, the field tests for seismic observation using i-jishin terminals were performed as described below.

4.1. Experiments in the Kanto Region

For studying the possibility of application of i-jishin terminals to strong-motion observation of buildings, the i-jishin terminals were placed on different floors in eight buildings (mainly houses of people involved in the development) with different structures of wooden, RC construction, SRC construction, and S construction in the prefectures of Ibaraki, Chiba, Tokyo, and Kanagawa. Observation has been performed since January 2011. Numerous seismic records corresponding to an seismic intensity of 6 lower at the maximum have been obtained including those of the 2011 off the Pacific coast of Tohoku Earthquake, which occurred on March 11. **Table 2** lists the observation points, while **Fig. 13** shows the observed intensity distribution.

4.2. Observation of Aftershocks in Tsukuba

Aftershocks of the 2011 off the Pacific coast of Tohoku Earthquake, which occurred on March 11, were observed in the adjoining multiple low-rise buildings of RC construction in Tsukuba City, Ibaraki Pref. Aftershock activities are intensive in this region, and monitoring was desired. However, seismographs were not installed because multiple issues such as installation cost, installation locations, and wiring were to be solved. i-jishin terminals, which overcome these issues, were used for the aftershock observation.

Observation was carried out in buildings of 2-3 story RC construction with different ages, as summarized in **Table 3**. i-jishin terminals were fixed to the floor surface of the different floors in each building, as shown in **Fig. 14**, in order to start the seismic observation from January 2012 onward.

Multiple seismic records corresponding to an seismic intensity of 4 at the maximum were obtained after the installation. The calculation results of the velocity response spectrum (damping constant, $h = 0.05$) based on these records showed that the amplitude of building K was the largest, as shown in **Fig. 15**, with a longer dominant frequency. The data obtained at the K-NET observation point (IBR011) close to the buildings are also included in this figure for the purpose of comparison.

In building K, structural damage was minor during the 2011 off the Pacific coast of Tohoku Earthquake, while multiple interior damages occurred, such as facility damage of the ceiling and damage of the finishing material on the wall, when compared with the other buildings. The difference in damages to the nonstructural members and construction facility was observed to be due to the difference in the natural period and deformation resulting

Table 2. Characteristics of the buildings.

Name of observation point	Structure	Total Floors	Installed Floors	Installed Areas
DRIP-0	SRC	15F	9F	Tsukuba
DRIP-2	SRC	10F	6F	Tsukuba
DRIP-3	Wooden	2F	2F	Tsukuba
DRIP-4	RC	5F	3F	Matsudo
DRIP-5	RC	3F	1F	Adachi
dmiPod	Wooden	3F	2F	Kunitachi
nakaPod	Wooden	2F	2F	Yokohama
yoiPod	Wooden	5F	2F	Tama

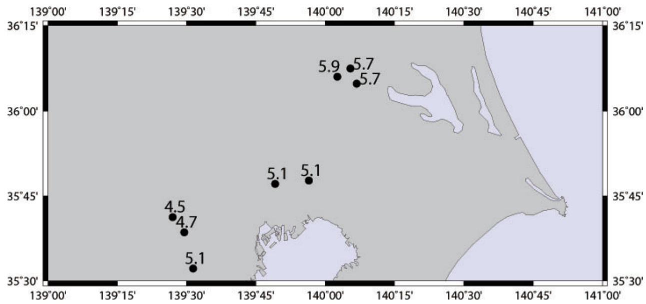

Fig. 13. Distribution of the intensities recorded at 2011/03/11 14:46.

Table 3. Characteristics of the buildings.

Contracted name of the building	Structure	Total Floors	Installed Floors	Building date
H	RC	3F	1F, 2F	1975
F	RC	3F	1F, 3F	1981
S	RC	2F	1F, 2F	1995
D	RC	2F	1F, 2F	1999
K	RC	3F	1F, 3F	2003

Fig. 14. Installation of "i-jishin."

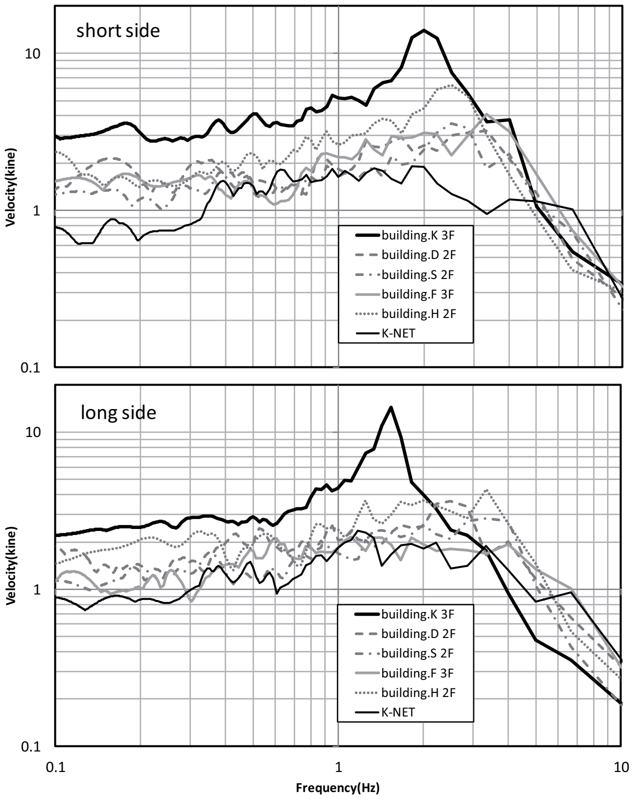

Fig. 15. Velocity response spectrum calculated from the waveforms recorded by the "i-jishin" terminals on each building (hypocenter: Chiba prefecture northeast, 2012/04/25 5:22, M5.5).

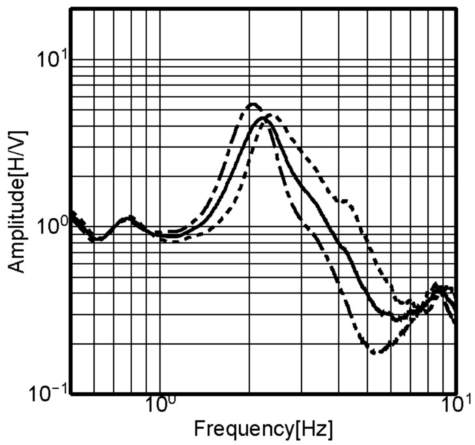

Fig. 16. H/V spectrum amplitude of K building recorded by JU-310 microtremor sensor (dashed line: long side, chained line: short side, solid line: composition).

from the difference in the various construction methods: a toughness-oriented rigid-frame structure with high deformation performance was used for building K; a strength-oriented structure with many earthquake-resisting walls was used for other buildings.

Microtremor observation was performed in each building using microtremor sensors (JU-310 manufactured by Hakusan Corporation). In the H/V spectrum ratio, the spectrum amplitude of building K at approximately 2-3 Hz is greater than that of the other buildings, as shown in **Fig. 16**, in accordance with the response spectrum obtained from the seismic observation results using i-jishin.

The response spectrum obtained from the seismic observation results using the i-jishin accords with the micrometer H/V spectrum ratio in the case of the other buildings.

Tremor Data View [14] was used for microtremor data analysis and study of the dominant frequency of the buildings using H/V spectrum ratio by referring to literature [15].

4.3. Experiments in Other Areas

Seismic observation using i-jishin has been performed in the following regions in an attempt to determine the issues concerning installation and local deployment.

In Nagaoka City, Niigata Pref, in collaboration with the community FM network, 10 i-jishin terminals were installed in the cabinets of broadcast facilities of the main center and satellite stations and houses of listeners who accepted the installation, and observation has been performed since January 2012. In Fujisawa City, Kanagawa Pref, in collaboration with a specified NonProfit Organization (NPO), the project asked individual local residents for installation and installed i-jishin terminals at 37 places in 21 permitted houses with building types of wooden, RC construction, and S construction, installation floors of 1^{st}-7^{th}, building age of before and after 1981, when the Japanese quake-resistance standards changed.

The comparison between the observation results and the ground model could easily be performed because a detailed ground model in a 50 meter mesh has been created in Fujisawa City. The terminals were therefore installed

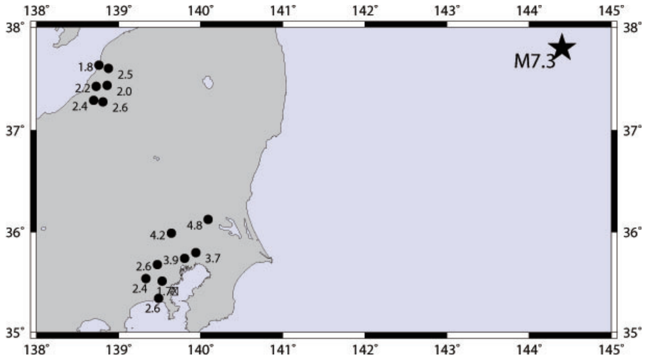

Fig. 17. Distribution of intensities recorded at 2012/12/07 17:18.

such that the difference in the amplitude rates on the surface layer is as large as possible for the existing ground model.

Observation began in January 2012, and terminals were installed with permission.

As of August 2013, multiple seismic records with an intensity of approximately 3 at the maximum, as shown in **Fig. 17**, were obtained in each of these regions.

Detailed installation locations are not disclosed in the geonavi site from the viewpoint of personal information protection, and data are monitored at a specific site.

Constant micrometer observation is performed using micrometer sensors on the ground close to the buildings and different floors of the buildings in parts of the installation locations, and the results of spectrum amplification obtained on the basis of the micrometer observation of the surface layer at the location of the buildings and the spectrum amplification within the buildings were plotted in a graph. Residents were taught the meanings of the graph, and they were highly impressed to know about the degree to which their own land and house are likely to be shaken by earthquakes. However, actual measurements such as seismic retrofit have not been taken thus far.

4.4. Problems Derived from the Experiments

Some issues were observed in the course of the field tests including the current experiments. Although error in the data records was generated because of problems such as compatibility of the iOS versions, correction was undertaken by upgrading the i-jishin app. However, such updating work and monitoring of normal operation of the app require maintenance personnel. The authors consider the environments in which users can spontaneously perform maintenance operations as important. To that end, a framework for the users to reap the benefits of installing i-jishin terminals is essential.

5. Future Development

5.1. i-jishin

The performance of the current i-jishin terminals is not effective for recording earthquakes with an seismic intensity of 2 or less on the Japanese scale. In other words, the records of frequent earthquakes with an seismic intensity of 1-2 among the earthquakes felt thus far have not been utilized. Therefore, when a framework for uploading the seismic data on a cloud server is developed by using more precise sensors, seismograph terminals affordable by general households are developed, observation is performed at more points, and more factors that lead to the promotion of earthquake-resisting construction are expected to be obtained. However, an issue that still remains to be solved is that the price of the terminals cannot be rapidly reduced in the current small market. The authors wish to appeal for the usefulness of a multipoint observation network using less expensive sensors.

Development of noise reduction methods for i-jishin terminals and a seismograph app operating in more popular Android terminals is also intended.

Needless to say, increasing the stability of the current i-jishin terminals as meters according to the upgraded version of the OS or hardware is important.

Development of technologies that enable the users to understand the strong-motion index such as seismic intensity in real time is also a subject of investigation in the future because it is a major factor of benefit for the users of i-jishin terminals.

5.2. Geonavi

With an expected increase in the number of terminals, more data will be uploaded on the server in the future. Development of processing technologies with regard to this data increase is urgent.

A framework with high usability for data users and operating administrators should be developed, allowing the administrators to control the disclosure level by account considering the viewpoint of personal information protection.

Providing Application Programing Interface (API) services for seismic observation records using i-jishin is the objective in the future. This makes it possible for seamless linkage of data between i-bidou [16], which automatically analyzes the uploaded microtremor observation records measured by nonexperts on cloud environments via mobile information terminals, J-SHIS [17], Japan seismic hazard Information station, and other systems. This results in the development of an observation system of hazard information considering the amplitude characteristics of the ground and buildings to broaden the possibilities of the usage of i-jishin terminals.

5.3. On-Site Experiments

The authors wish to perform field tests in more locations. Locations where seismic activities are intense and for which modeling of ground is available and data can be associated with the existing database are desirable; however, cooperation with the users via organizations such as local governments, private companies, and NPO is the most important factor. For this purpose, many issues are to be solved, such as network construction, maintenance operations, consideration of personal information protection when publishing data, and return of research outcome to those who accepted the installation.

The authors would like to be involved in activities for the promotion of earthquake-resisting renovation and increase in disaster prevention awareness by constantly observing microtremor of the ground and buildings near the installation locations of i-jishin and using the obtained results along with i-jishin seismic observation results. By doing so, a framework for observing the spectrum amplitude with regard to the ground and buildings can be constructed, and more accurate earthquake hazard risk information than currently published can be provided to the users.

Moreover, by effectively using tools such as i-jishin, i-bidou, and Japan seismic hazard Information station (J-SHIS), the authors will be engaged in sharing and usage of the seismic harzard and risk information.

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Name:
Shohei Naito

Affiliation:
Researcher, Disaster Risk Research Unit, Department of Integrated Research on Disaster Prevention, National Research Institute for Earth Science and Disaster Prevention (NIED)

Address:
3-1 Tennodai, Tsukuba, Japan

Brief Career:

2001 Master of Science, Ibaraki University
2002 Joined Hakusan Corp.
2009- Researcher, NIED

Selected Publications:

• S. Naito, H. Azuma, S. Senna, M. Yoshizawa, H. Nakamura, K. X. Hao, H. Fujiwara, Y. Hirayama, N. Yuki, and M. Yoshida, "On-site experiment of seismic monitoring network by utilization inside sensors of mobile terminal," Joint Symposium of Seismic Hazard Assessment, 2013.
• S. Naito, H. Azuma, S. Senna, M. Yoshizawa, H. Nakamura, H. Fujiwara, Y. Tanaka, and M. Yoshida, "Vibration test of the seismometer using mobile information terminal on the 3-D Full-Scale Earthquake Testing Facility," Japan Geoscience Union Meeting, 2012.
• S. Naito and H. Nakamura, "Experiment of Earthquake Early Warning system via the wireless communication network such as the WiMAX," Japan Geoscience Union Meeting, 2011.

Academic Societies & Scientific Organizations:

• Seismological Society of Japan (SSJ)
• Japan Association for Earthquake Engineering (JAEE)
• Japan Geoscience Union (JPGU)

Name:
Hiroki Azuma

Affiliation:
Researcher, Disaster Risk Research Unit, Department of Integrated Research on Disaster Prevention, National Research Institute for Earth science and Disaster Prevention (NIED)

Address:
Tennodai 3-1, Tsukuba, Ibaraki 305-0006, Japan

Brief Career:
2007 Master of Media and Governance, Keio University
2007- A TV Program Producer/Director
2010- NIED, producing mobile applications for disaster prevention, J-SHIS portal site

Selected Publications:
• Hiroki Azuma et al., "Continued effort for the Development of the i-Jishin cloud system," JpGU, 2011.

Academic Societies & Scientific Organizations:
• Information Processing Society of Japan (IPSJ)

Name:
Shigeki Senna

Affiliation:
Visiting Researcher, National Research Institute for Earth Science and Disaster Prevention (NIED)

Address:
3-1, Tennodai, Tsukuba, Ibaraki 305-0006 Japan

Brief Career:
1994 Joined Dia Consultants Corporation
2003-2009 Researcher, National Research Institute for Earth Science and Disaster Prevention (NIED)
2009- Visiting Researcher, National Research Institute for Earth Science and Disaster Prevention (NIED)

Selected Publications:
• "Liquefaction Damage of The Tonegawa Basin Caused by The 2011 off the Pacific coast of Tohoku Earthquake" Journal of Japan Association for Earthquake Engineering, Vol.12, No.5, pp. 143-162, 2012.
• "Estimation of spectral amplification of ground motion based on geomorphological land classification" Journal of Japan Association for Earthquake Engineering, Vol.9, No.4, pp. 11-25, 2009.

Academic Societies & Scientific Organizations:
• The Seismological Society of Japan (SSJ)
• Japan Association for Earthquake Engineering (JAEE)
• The Society of Exploration Geophysicists of Japan (SEGJ)

Name:
Mutsuhiro Yoshizawa

Affiliation:
Chief Researcher, Research and Development Institute, Takenaka Corporation

Address:
1-5-1 Otsuka, Inzai, Chiba, Japan

Brief Career:
1992 Joined Takenaka Corp
2010 Loan to Hyogo Earthquake Engineering Research Center, NIED
2013 Research and Development Institute, Takenaka Corporation

Selected Publications:
• "Seismic Loss of Functionality in High-Rise and Low-Rise Office Buildings: The 2011 E-Defense shaking table test," Proceedings of 15th World Conference on Earthquake Engineering, Paper No.3977, 10p., Lisbon, Sep. 2012.

Academic Societies & Scientific Organizations:
• The Architectural Institute of Japan (AIJ)
• The Japanese Geotechnical Society (JGS)

Name:
Hiromitsu Nakamura

Affiliation:
Senior Researcher, Department of Integrated Research on Disaster Prevention, National Research Institute for Earth Science and Disaster Prevention

Address:
3-1 Tennodai, Tsukuba, Ibaraki 305-0006, Japan

Brief Career:
2001- Researcher, Railway Technical Research Institute
2006- Researcher, NIED
2008- Senior Researcher, NIED
2012- Deputy Project Director, Department of Integrated Research on Disaster Prevention, NIED

Selected Publications:
• H. Nakamura and T. Miyatake, "An approximate expression of slip velocity time function for simulation of near-filed strong ground motion," Zisin, Vol.53, pp. 1-9, 2000.
• H. Nakamura, S. Horiuchi, C. Wu, S. Yamamoto, and P. A. Rydelek, "Evaluation of the real-time earthquake information system in Japan," Geophysical Research Letters, Vol.36, L00B01, 2009.

Academic Societies & Scientific Organizations:
• Seismological Society of Japan (SSJ)

Name:
Ken Xiansheng Hao

Affiliation:
Principal Research Fellow, National Research Institute for Earth Science and Disaster Prevention

Address:
3-1 Tennodai, Tsukuba 305-0006, Japan

Brief Career:
1992-1997 Research Engineer, Research Institute, Taisei Corporation, Japan
1997-1999 Research Associate, University of British Columbia, Canada
2005- Senior Researcher, NIED, Japan

Selected Publications:
- K. X. Hao, H. Si, H. Fujiwara, and T. Ozawa, "Coseismic surface-ruptures and crustal deformations of the 2008 Wenchuan earthquake Mw7.9, China," Geophys. Res. Lett., Vol.36, L11303, doi:10.1029/2009GL037971, 2009.
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Academic Societies & Scientific Organizations:
- Scientific Board member of Global Earthquake Model
- America Geophysical Union (AGU)
- Japanese society for Active Fault Studies (JSAFS)
- Seismological Society of Japan (SSJ)

Name:
Hiroyuki Fujiwara

Affiliation:
Director, Department of Integrated Research on Disaster Prevention, National Research Institute for Earth Science and Disaster Prevention

Address:
3-1 Tennodai, Tsukuba, Ibaraki 305-0006, Japan

Brief Career:
1989- Researcher, NIED
2001- Head of Strong Motion Observation Network Laboratory, NIED
2006- Project Director, Disaster Prevention System Research Center, NIED
2011- Director, Social System Research Department, NIED

Academic Societies & Scientific Organizations:
- Seismological Society of Japan (SSJ)
- Japan Association for Earthquake Engineering (JAEE)

Name:
Yoshiharu Hirayama

Affiliation:
Chief Research Engineer, Hakusan Corporation

Address:
J Tower, 1-1, Nikkou-cho, Fuchu-shi, Tokyo 183-0044, Japan

Brief Career:
1991-1994 Doctor Course, Department of Earth Physics, Faculty of Science, University of Tokyo, Japan
1994 Dr. Sci.
1994- Researcher of Earthquake Research Institute, University of Tokyo
1996- Hakusan Corporation

Selected Publications:
- "A Sharing System on Earthquake Response Information of Buildings Using a Sensor Cloud Technology," Journal of Japan Association for Earthquake Engineering, Vol.13, No.5, pp. 44-61, Nov., 2013.

Academic Societies & Scientific Organizations:
- Seismological Society of Japan (SSJ)
- Japan Geoscience Union (JpGU)
- Architectural Institute of Japan (AIJ)

Name:
Noboru Yuki

Affiliation:
Manager, R&D Department, Hakusan Corporation

Address:
J-Tower, 1-1 Nikkou-cho, Fuchu-shi, Tokyo 183-0044, Japan

Brief Career:
1987 Joined Advanced Control Laboratory, Inc.
2001- Joined Hakusan Corp.

Selected Publications:
- "A Sharing System on Earthquake Response Information of Buildings Using a Sensor Cloud Technology," Journal of Japan Association for Earthquake Engineering, Vol.13, No.5, pp. 44-61, Nov., 2013.

Name:
Minoru Yoshida

Affiliation:
CEO, Hakusan Corporation

Address:
1-1 J-Tower, Nikko-cho Fuchu, Tokyo 183-0044, Japan

Brief Career:
1983 Joined National Institute of Polar Research
1986- Founded Hakusan Corp.

Selected Publications:
- "Development of Brand-new Portable Earthquake Simulator Using Holonomic Omni-directional Platform," JSME, Journal of the JSME, Vol.114, No.1111, pp. 448-449, Jun., 2011

Academic Societies & Scientific Organizations:
- Japanese Society of Snow and Ice (JSSI)
- Architectural Institute of Japan (AIJ)