Seismic monitoring and early damage assessment systems in Japan

Fumio Yamazaki
Institute of Industrial Science, University of Tokyo, Japan

Summary

Recent developments of seismic monitoring systems and early damage assessment systems in Japan are reviewed. National and local governments in Japan have deployed numerous seismic instruments for the purpose of disaster management, mostly after the 1995 Kobe earthquake. Utility companies and highway authorities have also established seismic networks in order to use earthquake information for supply or traffic control just after the occurrence of an earthquake. Based on the collected seismic information and the GIS-based inventory data, held on computer, early damage assessments are conducted and the results are used for emergency management at the stage when actual damage information is scarce. In this paper, typical seismic networks and early damage assessment systems recently developed in Japan are presented and their roles in disaster management and future directions are discussed.

KEY WORDS: seismic monitoring; seismometer networks; damage assessment; disaster management; GIS; lifeline systems

Prog. Struct. Engng Mater. 2001; **3**: 66–75 (DOI: 10.1002/pse.75)

Introduction

The Kobe (Great Hanshin, Hyogoken-Nanbu) earthquake on 17 January, 1995 caused serious damage to infrastructure and buildings in the highly populated area of central-western Japan. Over 5000 people were killed as a direct result[1]. Just after the occurrence of the earthquake, information on structural damage and casualties was not obtainable from the hard-hit areas, owing to the loss of urban functions, especially electric power outage, overload of telecommunication lines, and damage to traffic systems. One of the most important lessons learned from this disaster is that the lack of information at an early stage causes significant delays to emergency response activities.

After this earthquake, countermeasures against earthquakes were given higher priority than before. In order to obtain a detailed and accurate shake map from an earthquake, thousands of strong-motion seismometers have been deployed throughout Japan[2], notably the seismic intensity meter networks of the Japan Meteorological Agency (JMA) and the Fire and Disaster Management Agency (FDMA). These networks successfully recorded the strong jolts of the Tottori-ken Seibu earthquake on 6 October 2000.

A number of damage assessment systems have also been developed by different organizations using the instrumental seismic intensity and magnitude data from the JMA or peak ground motion indices from their own seismometer networks. The geographic information system (GIS) is used as a platform for damage assessment, and loss estimation can be conducted for both actual and simulated events on such systems. However, in order to get accurate results, detailed inventory data and accurate vulnerability functions should be employed in the estimation.

Recently, utility companies and highway authorities in Japan have also been strengthening their seismic countermeasures. The first early damage assessment system for lifeline systems may be SIGNAL (the seismic information gathering and network alert) of the Tokyo Gas Company, which has been in actual operation since 1994[3]. SIGNAL performs damage estimation of the natural gas network based on its extensive seismic monitoring and GIS. Together with actual damage reports, the result of the damage estimation will be used for deciding whether or not to shut off the gas supply to avoid secondary disasters in a seismic event.

In order to gather earthquake information at an early stage and to establish prompt, efficient traffic control, the Japan Highway public corporation (JH) had deployed over 100 accelerometers along its expressways before the Kobe earthquake. The number of instruments was increased more than three-fold after the earthquake[4]. Using the peak ground motion indices from these instruments, JH closes expressways or reduces the maximum speed limit for safety inspection of roadways. Owing to the increased

number of instruments, the number of expressway closures has increased recently, mostly associated with no damage. Hence, an examination of traffic regulation criteria is needed.

This review paper introduces recent typical seismic networks and early damage assessment systems in Japan, and their roles in disaster management and future directions are discussed.

National seismic monitoring systems in Japan

Although there were many more seismometers in Japan than anywhere else in the world, only a few were located in the hardest-hit belt in the Kobe area at the time of the 1995 earthquake[5]. Installation of new seismometers was greatly increased after the earthquake.

The JMA is in charge of earthquake-related information in Japan. Since 1987, it has been deploying new JMA-87-type accelerometers[6] at recording stations throughout Japan. In 1993 and 1994, several damaging earthquakes occurred in northern Japan[7]. Hence, mainly for the purpose of early tsunami warning the number of seismic stations was increased to 268. After the Kobe earthquake, in order not to miss localized heavily damaged areas, the number of stations was further increased to 574 in 1996. New instruments installed at these stations measure a three-component acceleration time history and calculate the instrumental JMA seismic intensity[8] on site. Note that the basis of the JMA seismic intensity changed from human judgement to instrumental measurement about ten years ago. It is uniquely assigned from a three-component acceleration record, regardless of human subjectivity or characteristics of the surrounding built environment.

Using time history records from several stations, the JMA determines the location and magnitude of an event within a few minutes. The instrumental JMA intensity values at the 574 stations are also collected by JMA's telecommunication network at headquarters and disseminated nationwide through mass media. The event information and intensity data are also posted on the web site (http://tenki.or.jp/quake. html) shortly after the occurrence of an earthquake. Because the telecommunication line connected to the JMA Kobe station was affected by the Kobe earthquake, the JMA recently strengthened the telecommunication network with a satellite backup system.

After the Kobe earthquake, the National Research Institute for Earth Science and Disaster Prevention (NIED) of the Science and Technology Agency, Japan deployed a total of 1000 strong-motion accelerometers throughout Japan[9]. This 'Kyoshin Net' or 'K-NET' has stations at an average separation of 25 km. The instruments are placed on free field with a common specification, and geological investigations have been carried out for all the sites. Each instrument has two telecommunication ports, one directly connected to a modem belonging to the local municipality and another connected to the K-NET control centre at NIED. After receiving seismic event information from the JMA, the control centre acquires time history records and puts them on the Internet (http://www.k-net.bosai.go.jp). The primary role of K-NET is accumulation of strong-motion data for scientific research and disaster management.

The FDMA has also ventured upon a project to deploy one accelerometer in each municipality (3255 in total) in Japan, excluding municipalities already having JMA and K-NET instruments. Using this monitoring system, the distribution of strong ground motion can be estimated, even in a very localized event. Once an earthquake occurs, the FDMA control centre will collect the JMA seismic intensities through a digital telecommunication network. The FDMA and the JMA exchange their collected data through private communication lines, and the real-time seismic information is used for identifying affected areas and preparing for crisis management.

Fig. 1 shows the distribution of JMA seismic intensity in the 2000 Tottori-ken Seibu earthquake. By means of the enhanced national seismic networks, the distribution of seismic intensity could be captured in much more detail than before. The seismic information was promptly used for the preparation of emergency response at national and prefectural levels. Although the magnitude of the Tottori earthquake on the JMA scale is 7.3, bigger than that of the 1995 Kobe earthquake (7.2), the damage was much smaller and, fortunately, no casualty was associated with it.

Loss estimation methods and systems

Loss estimation is an important element of assessing and reducing the effects of earthquakes. Fig. 2 shows the steps in assessing and mitigating losses due to natural disasters. In the United States, the methodology of earthquake loss estimation has been embodied in GIS software called HAZUS[10, 11]. But the collection of building inventory for the entire USA requires enormous efforts, and its application is still limited to particular areas.

Methods of loss estimation are basically the same for pre-event and post-event phases. Fig. 3 compares the steps of seismic loss estimations for scenario earthquakes (pre-event) and for actual earthquakes (post-event). The only difference may be the accuracy of earthquake ground motion estimation. The distribution of earthquake ground motion is estimated by various empirical or analytical methods for scenario earthquakes, but by interpolation of observed values for actual events, in most real-time or near-real-time damage assessment systems. Hence, the estimated ground motion distribution is obtainable

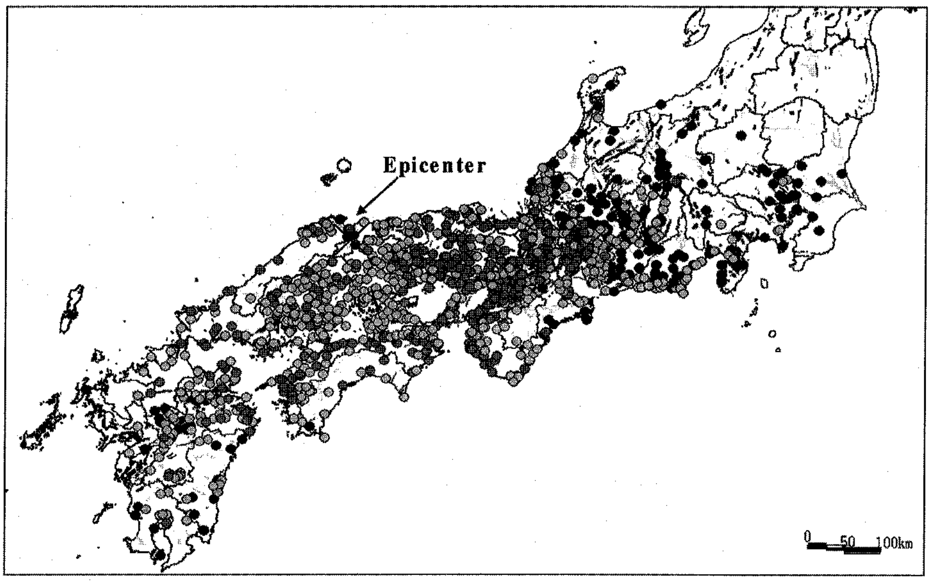

Fig. 1 JMA instrumental seismic intensity recorded by national seismic networks in the Tottori-ken Seibu earthquake, 6 October 2000

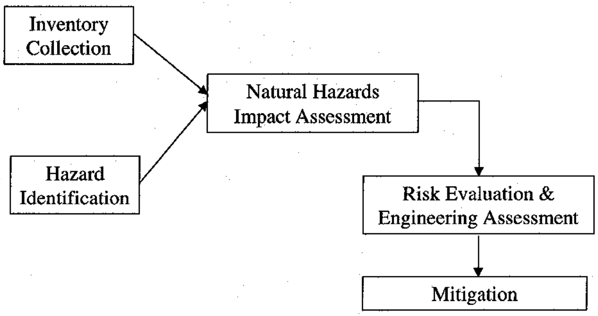

Fig. 2 Steps in assessing and mitigating losses due to natural disasters [10]

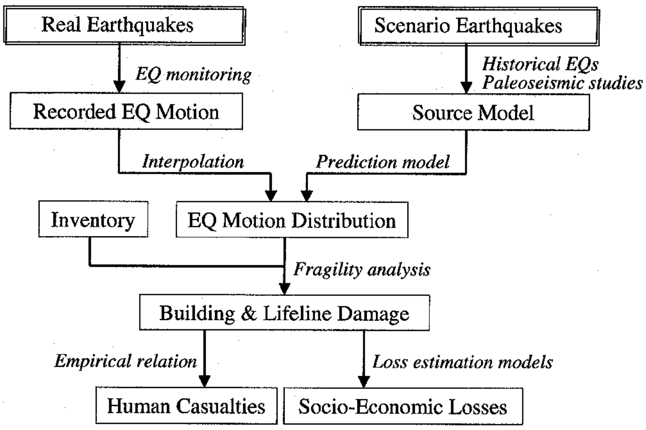

Fig. 3 Comparison of the flows of seismic loss estimation for scenario earthquakes and for actual earthquakes

with higher accuracy in the post-event phase. However, dense seismic monitoring and spatial data on site amplification are required for this. In this regard, the Digital National Land Information (DNLI), a GIS-based database covering the whole of Japan with a 1 × 1 km mesh, is used in Japan as a method to estimate site amplification characteristics[12,13]. Geomorphological and geological information included in the DNLI was compared with seismic records[6] and site amplification ratios were assigned for these sub-surface classifications.

As an example, the distribution of the JMA seismic intensity in the 2000 Tottori earthquake was estimated by a spatial interpolation technique named Kriging[14], and the result is shown in Fig. 4. In the Kriging technique, values are obtained at the observation points, and, between these points, stochastic interpolation consisting of the trend (mean) and random components gives an estimation of the spatial distribution. We introduced an attenuation relationship derived from observed records as the trend component[4], hence the estimated intensity distribution looks quite natural. Obviously, the accuracy of the estimation depends on the density of instruments. At locations far from the observation points, the estimation approaches the trend component with large randomness.

As shown in Fig. 3, the next step of loss estimation is damage assessment for buildings and/or lifelines. Fragility curves (vulnerability functions) and inventory data are most important in this step. Fragility curves, which correlate a strong-motion index and probability of damage for a certain class of structures, are developed, mostly based on empirical data. Fig. 5 plots fragility curves of buildings in Japan, which were developed from building damage data in the Kobe earthquake[15]. The structural type and period of construction are important factors to determine the damage probability. Since the fragility curves shown here use ample and reliable data sets of building damage and inventory, their accuracy is supposed to be much higher than that of existing ones. But we must admit a limitation of the empirical approach; the functions are affected by the regional characteristics of buildings in the Kobe area and the

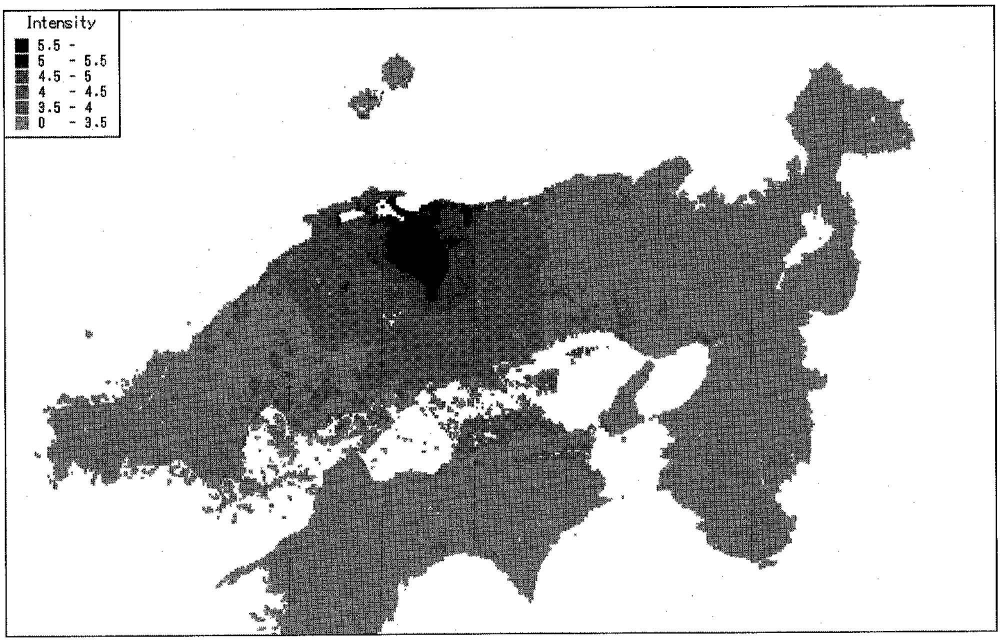

Fig. 4 Distribution of JMA seismic intensity in the 2000 Tottori earthquake estimated by the Kriging technique.

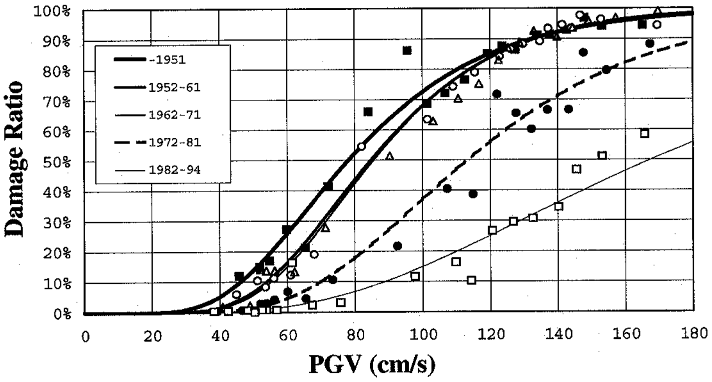

Fig. 5 Fragility curves for wood-frame buildings in Japan, of different construction periods; developed using damage data from the Kobe earthquake [15]. Curves indicate the cumulative probability of severe damage as a function of peak ground velocity (PGV)

characteristics of seismic motion in the Kobe earthquake. Hence, if we use empirical fragility curves for other areas or events, we must be cautious about the variation of results estimated from such parameters.

The National Land Agency, which is in charge of disaster management by the Japanese government, developed an early damage assessment system and began operation in 1996[16]. Using intensity and event information from JMA and GIS data for the whole of Japan, on a 1 × 1 km mesh, this system estimates the seismic intensity, the number of severely damaged buildings, and the number of deaths due to the collapse of buildings in each pixel, by simplified empirical relations. These relations are highly dependent on the data from the 1995 Kobe earthquake. This system is available on the Internet (http://www.nla.go.jp).

For the 2000 Tottori earthquake, the numbers of severely damaged buildings and casualties estimated by the system were over 6000 and over 200, respectively. Actually, they were about 400 and 0, respectively. This fact indicates that the results of loss estimation, in general, contain a significant amount of variation, as mentioned before. Especially, the casualty estimation is uncertain because it is carried out by a multi-step estimation (Fig. 3) and it is highly affected by the natural and built environments and social conditions of the area hit by an earthquake, and by the time of day and season of the occurrence[1].

Although early damage assessment based on seismic monitoring and GIS is still useful to prepare for crisis management, gathering information on actual damage at an early stage is necessary. In this regard, advanced technologies, such as airborne and space-borne remote sensing[17,18], global positioning system (GPS) and mobile communication tools, are promising for the near future. In an attempt to investigate the possibility of automated detection of damaged buildings from aerial television, the characteristics of high-definition television (HDTV) images taken after the 1995 Kobe earthquake were investigated[18]. The relationships between the degree of building damage and the colour indices and edge intensity of the aerial images were examined by image processing techniques[19]. The characteristics of building damage were defined on the basis of hue, saturation, brightness and edge intensity. Using the threshold values of these parameters, typical areas were divided into damaged and undamaged pixels. A texture analysis was further conducted on these pixels, and damaged buildings were identified, as shown in Fig. 6. The damage distribution extracted by the proposed method agreed well with ground truth data and visual inspection of the HDTV images.

Seismic monitoring and damage assessment system for city gas networks

In the Kobe earthquake, the natural gas system in the area was seriously affected[20]. Numerous breaks in distribution and service pipes were reported and the Osaka Gas Company stopped gas supply for 860 000 customers in the hard-hit areas. However, it took 6–15 h before the decision to shut off supply was made because the collection of information on the extent of damage was extremely difficult immediately after the earthquake. Owing to the massive damage to gas pipes and disruption of road networks, service restoration took about 3 months.

To cope with secondary disasters, e.g. fires and explosions, after earthquakes, city gas utilities in Japan have promoted various safety countermeasures in the last decade. Fig. 7 shows the emergency shut-down systems of the Tokyo Gas Company with 8.7 million metered customers. The gas pressure and flow of production facilities and high-pressure (HP) pipelines are constantly monitored by operators. Remote-control emergency shut-off valves are installed in primary facilities, such as governor stations and gas holders. Segmentation of gas networks is carried out at two levels: one for medium-pressure (MP) lines and another for low-pressure (LP) lines. Emergency shut-off of gas networks can be carried out for these

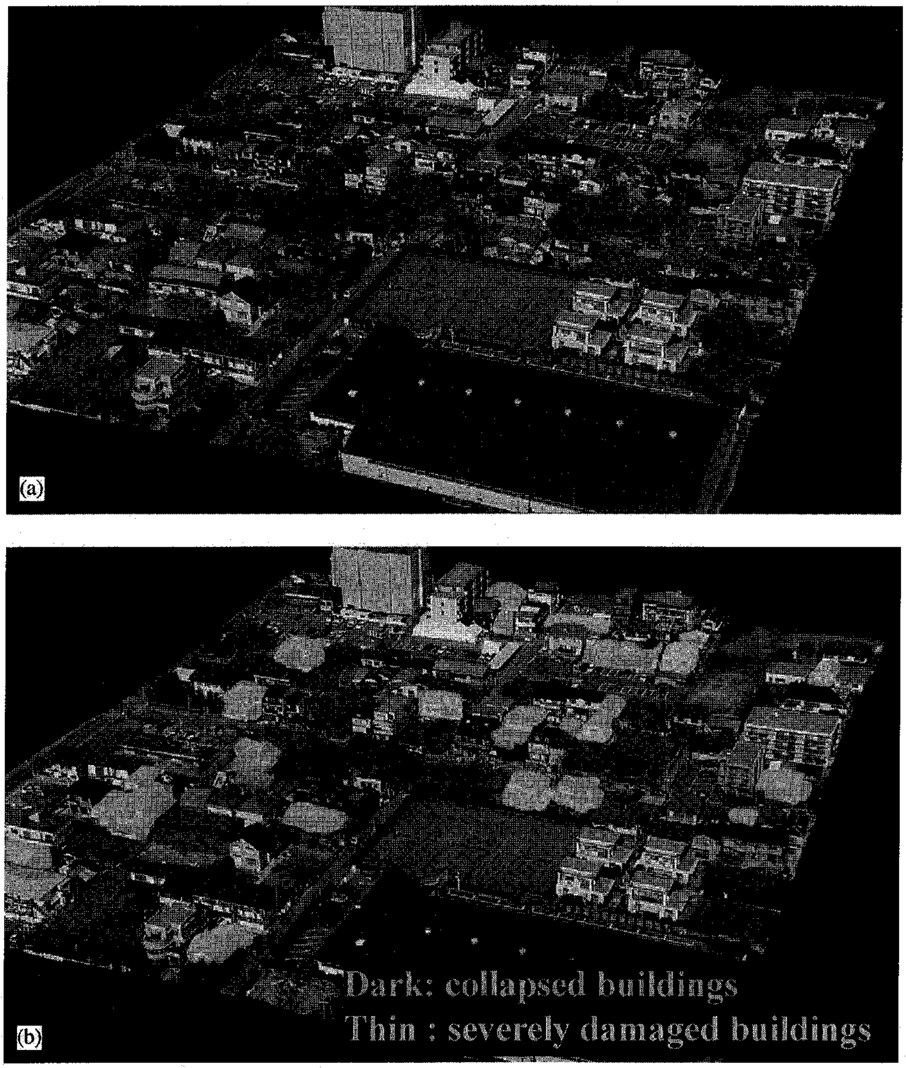

Fig. 6 (a) The result of automated building damage detection — HDTV image taken after the 1995 Kobe earthquake; (b) results of visual inspection and field survey

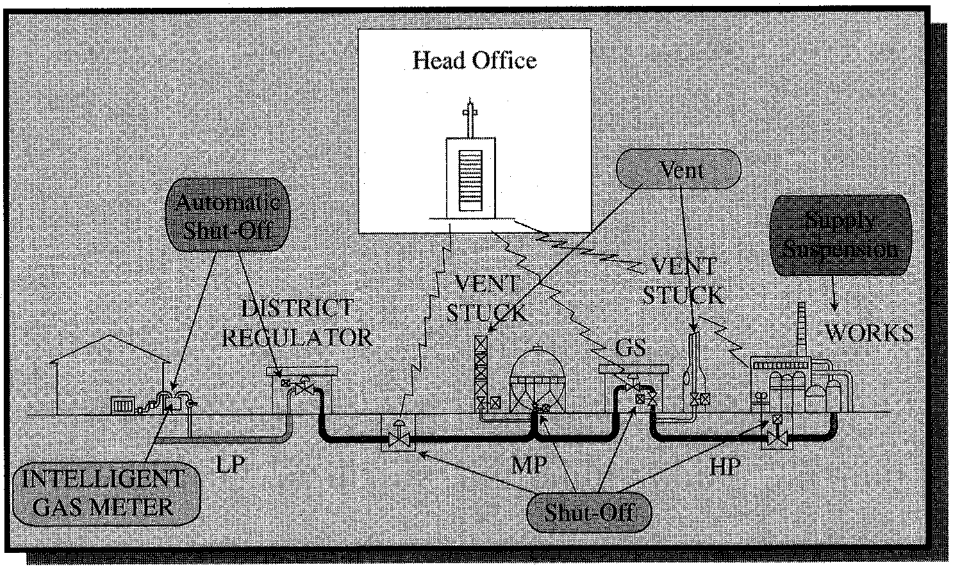

Fig. 7 Emergency shut-off systems of natural gas supply, Tokyo Gas [23]

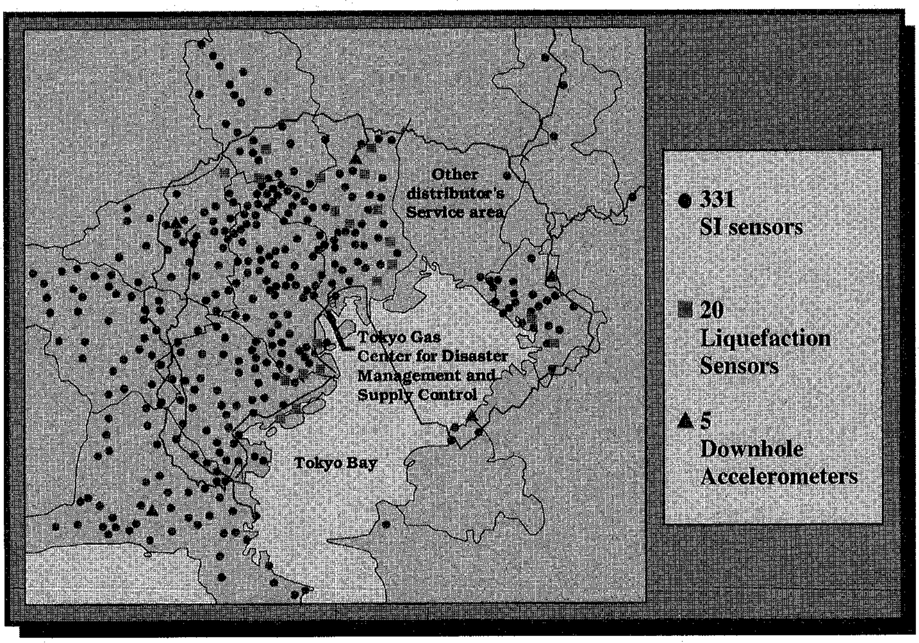

Fig. 8 Distribution of seismic sensors in the SIGNAL system, greater Tokyo area [3]

units, called K-blocks for MP lines and L-blocks for LP lines. At each customer site, an intelligent gas meter stops the gas supply automatically if seismic motion larger than about 0.2 G is detected.

For LP lines, emergency shut-off is carried out automatically, based on measured values of the spectrum intensity (SI, the velocity response spectrum with 20% damping, averaged over the structural period between 0.1 and 2.5 s) at district regulator stations. Note that, based on lessons from recent earthquakes, new regulations on gas supply suspension in earthquakes have been issued by the Ministry of International Trade and Industry (MITI). According to the new regulations, gas supply must be suspended if an SI value equal or larger than 60 cm/s is observed, and particular attention should be paid to SI value exceeding 30 cm/s.

However, for MP lines, an automated shut-off system is difficult to install because the service areas and the effects of emergency shut-off are much larger than for LP lines. It is also hard to detect pipe breaks from changes of gas flow and pressure because pipe breaks and automated shut-offs may be confused. Therefore, the early damage assessment system SIGNAL was introduced with 331 SI sensors[21] in 1994 (Fig. 8). The SI sensors measure the peak ground acceleration (PGA) and the spectrum intensity. The SI and PGA values measured at district regulator stations are sent by the company's radio to the supply control centre. SIGNAL performs damage estimation for pipes and customers' buildings, using GIS-based inventory data and measured strong-motion indices[3]. Together with actual damage reports, the results of the damage estimation are used to decide whether or not to shut off the gas supply. Information on SIGNAL and the recorded PGA and SI values from recent earthquakes are available from the homepage of Tokyo Gas (http://www.tokyo-gas.co.jp/signal).

More recently, Tokyo Gas has developed a new SI sensor[22], having several new functions, but a much lower price. The new SI sensor can store acceleration time histories in its IC memory and send monitored strong-motion indices through public telecommunication lines. The new sensors will be installed at all the 3700 district regulator stations by 2007. The new SI sensor network is named SUPREME (super-dense real-time monitoring of earthquakes), and may be the densest seismic monitoring network in the world[23]. The data from the sensors will be used for early damage assessment of the city gas network, and the results will provide important information on seismic safety of the network.

Seismic monitoring and control of expressway networks

Recent earthquakes in Japan and USA, notably the 1989 Loma Prieta, 1994 Northridge and 1995 Kobe earthquakes, demonstrated the vulnerability of urban expressway structures to strong seismic motion. Hence the seismic countermeasures to expressway systems became one of the most important issues facing highway authorities. Seismic retrofit of bridges was carried out, both in the USA and in Japan as a prioritized project. Together with such mitigation measures, rapid traffic control soon after the occurrence of an earthquake is important to avoid secondary disasters, such as cars colliding with collapsed sections of bridges. For this task, seismic monitoring systems have been introduced by several highway authorities in Japan.

The Japan Highway public corporation (JH) owns expressway networks with a total length of 6615 km. In order to gather earthquake information at an early stage and to establish efficient traffic control, JH had deployed 123 accelerometers along its expressways (one instrument per 40 km) before the 1995 Kobe earthquake. JH further deployed 202 new seismometers along its expressways (one instrument per 20 km in addition to the existing ones) after the Kobe earthquake (Fig. 9). The new instruments can measure SI and instrumental JMA seismic intensity as well as PGA. Using the seismic information from these instruments, transmitted through its own telecommunication lines, JH closes expressways if a PGA value equal or larger than $80\ \text{cm/s}^2$ is recorded in the corresponding section, or reduces the maximum speed limit if PGA is equal or larger than $50\ \text{cm/s}^2$[4]. These traffic regulations continue until safety inspection of the roadway has been completed.

But these current regulation criteria need to be examined with respect to the increase in the number of instruments, the higher sensitivity of new instruments and recent experience of damaging and non-damaging earthquakes. In recent years, more than ten closures are conducted annually, but damage to expressway structures is almost unknown, except for a few damaging events of moderate to large magnitude. Public opinion demanded a means of avoiding

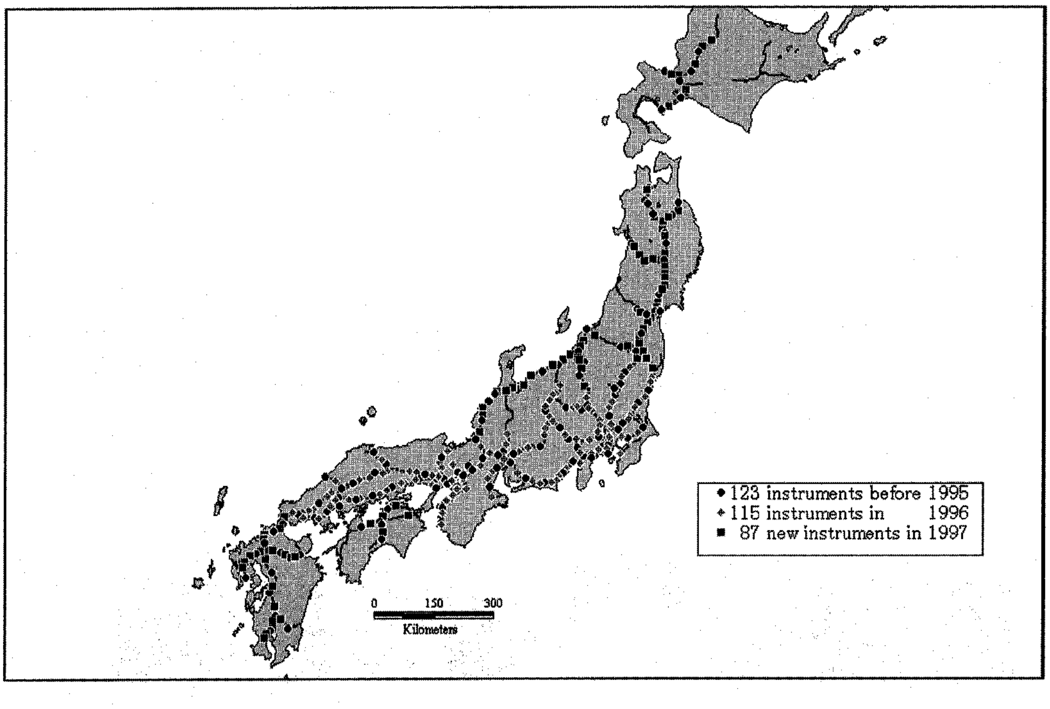

Fig. 9 Location of accelerometers for expressway networks in Japan [4]

unnecessary expressway closures without reducing safety levels. Hence, it is important to clarify the relationship between seismic damage to expressway structures and the strong ground motion indices[4]. To this end, the damage data for JH expressway structures in the recent earthquakes were collected and the ground motion indices along the expressways were estimated, based on observed records, by the Kriging technique. Comparing these results, fragility curves (vulnerability functions) for the expressway structures (bridges and elevated structures) in Japan were developed as shown in Fig. 10. The resultant fragility curves show that collapse or severe damage is not likely below the PGA values currently used for traffic control in Japan. These fragility curves can be used both for early post-event damage estimation and for pre-event risk assessment of expressway structures.

For traffic control of expressways immediately after an earthquake, the effect of seismic motion on automobile driving should also be considered, as well as structural damage. Some drivers who experienced the Kobe earthquake on expressways reported that control of their vehicles was almost impossible during strong jolts. Even though expressway structures have been retrofitted, traffic accidents associated with shaking might occur. Together with information transmission to drivers on expressways, research on this topic may be necessary.

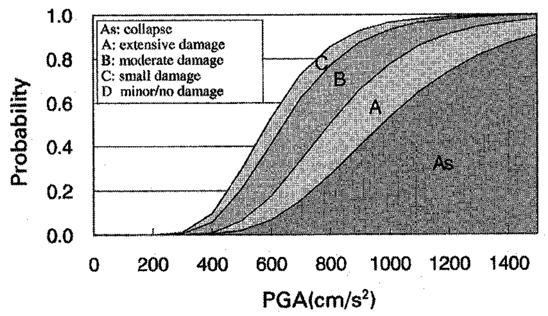

Fig. 10 Fragility curves of expressway bridge structures in terms of peak ground acceleration (PGA) derived from damage data due to the Kobe earthquake [4]

In this regard, the present author recently began an investigation of driver response under strong seismic motion[24], using a driving simulator Fig. 11. The simulator has six actuators and can simulate vehicle motion with six degrees of freedom[25]. The front view from the driver's seat is realized on three large screens with LCD projectors, and the sounds and small vibrations of a real car are also modelled in the simulator. The dynamic response of the virtual vehicle is simulated by the four-wheel, magic-formula model[26]. A model expressway course is incorporated in the simulator for virtual driving. The control system of the simulator was modified so that seismic motion can be applied to the model car through the actuators, together with the car's own acceleration. The virtual driving experiment is expected to provide useful information on the effects of shaking while driving automobiles at high speed. In the near future, intelligent transport systems (ITS) will use such data to control vehicles in natural hazards.

Conclusions

Recent developments in seismic monitoring systems and early damage assessment systems in Japan have been reviewed. One of the important lessons learned from the 1995 Kobe earthquake is that lack of

Fig. 11 Driving simulator for experiments on the effect of seismic motion on vehicle at control high speed

information at an early stage causes significant delays to disaster management. In order to obtain a detailed and accurate shake map from an earthquake, thousands of strong-motion seismometers have been deployed throughout Japan. These networks are considered to be important sources of information from the areas affected by seismic disasters.

A number of damage assessment systems have been developed on a GIS platform, using inventory data and vulnerability functions. Loss estimation can be conducted both for actual earthquakes using real-time seismic data and for scenario events, using predicted strong-motion distributions. The results of estimation are used for emergency management at the stage when actual damage information is scarce, but, for accurate estimations, detailed inventory data and accurate vulnerability functions should be employed. In this sense, the empirical relations developed from data from the 1995 Kobe earthquake have not given good estimates of the damage due to the 2000 Tottori earthquake. The importance of gathering actual damage information by means of advanced technologies such as remote sensing is also highlighted.

Utility companies and highway authorities have also established seismic networks to use earthquake information for supply or traffic control after an earthquake. Tokyo Gas has developed an early damage assessment system SIGNAL, based on extensive seismic monitoring and GIS. SIGNAL performs damage estimation of the natural gas network soon after the occurrence of an earthquake, and the result will be used for deciding, whether or not to shut off the gas supply to avoid secondary disasters. The system is currently being expanded to an enhanced seismic monitoring and decision support system.

The Japan Highway public corporation has also deployed many accelerometers along its expressways, in order to gather earthquake information at an early stage and to establish efficient traffic control. Using the peak ground motion indices from these instruments, JH closes expressways or reduces the maximum speed limit for safety control of roadways. However, examination of the traffic regulation criteria is still needed to incorporate the experience gained from recent earthquakes. The effect of seismic motion on vehicle control is suggested as a new topic of highway safety, in addition to the seismic performance of structures.

Although Japan was relatively well prepared for earthquake disasters, the damage in the Kobe earthquake was much more than expected, and the weakness of crisis management in Japan was exposed. Various new disaster mitigation measures have been established after the event, but future disasters may reveal other, unexpected weaknesses in the system. Continuous efforts to mitigate and to prepare for future disasters are essential.

References and recommended reading

[1] Yamazaki F, Nishimura A & Ueno Y. Estimation of human casualties due to urban earthquakes. *Proceedings of the 11th World Conference on Earthquake Engineering.* 1996. CD-ROM.

[2] Yamazaki F, Noda S & Meguro K. Developments of early earthquake damage assessment systems in Japan. *Structural Safety and Reliability: Proceedings of the 7th International Conference on Structural Safety and Reliability.* 1998; 1573–1580.

[3] Yamazaki F, Katayama T & Yoshikawa Y. On-line damage assessment of city gas networks based on dense earthquake monitoring. *Proceedings of the 5th US National Conference on Earthquake Engineering* 1994: **IV**: 829–837.

[4] Yamazaki F, Motomura H & Hamada T. Damage assessment of expressway networks in Japan based on seismic monitoring. *Proceedings of the 12th World Conference on Earthquake Engineering.* 2000. CD-ROM.

[5] Yamaguchi N & Yamazaki F. Estimation of strong motion distribution in the 1995 Kobe earthquake based on building damage data. *Earthquake Engineering and Structural Dynamics* 2001: **30**: 787–801.

[6] Molas GL & Yamazaki F. Attenuation of earthquake ground motion in Japan including deep focus events. *Bulletin of the Seismological Society of America* 1995: **85**(5): 1343–1358.

[7] Yamazaki F, Meguro K, Tong H & Katayama T. Review of recent five damaging earthquakes in Japan. *Proceedings of the Pacific Conference on Earthquake Engineering* 1995: **2**: 283–292.

[8] Shabestari KT & Yamazaki F. Attenuation relationship of JMA seismic intensity using recent JMA records. *Proceeding of the 10th Japan Earthquake Engineering Symposium* 1998: **1**: 529–534.

[9] Kinoshita S. Kyoshin Net (K-NET). *Seismological Research Letters* 1998: **69**(4): 309–332.

[10] National Institute of Building Sciences. *Earthquake Loss Estimation Methodology: HAZUS User's Manual.* 1997.

[11] Whitman RV, Anagnos T, Kircher CA, Lagorio HJ, Lawson RS & Schneider P. Development of a national earthquake loss estimation methodology. *Earthquake Spectra* 1997: **13**(4): 643–661.

[12] Matsuoka M & Midorikawa S. GIS-based integrated seismic hazard mapping for a large metropolitan area. *Proceedings of the 5th International Conference on Seismic Zonation* 1995: **II**: 1334–1341.

[13] Yamazaki F, Wakamatsu K, Onishi J & Shabestari KT. Relationship between geomorphological land classification and site amplification ratio based on JMA strong motion records. *Soil Dynamics and Earthquake Engineering*, Elsevier, 2000: **19**(1): 41–53.

[14] Cressie N. *Statistics for Spatial Data.* Revised edn. Wiley. 1993.

[15] Yamazaki F & Murao O. Vulnerability functions for Japanese buildings based on damage data due to the 1995 Kobe Earthquake. *Implications of Recent Earthquakes on Seismic Risk: Innovation in Structures and Construction* **2**. London: Imperial College Press. 2000: 91–102.

[16] Okayama K. Earthquake disaster countermeasures in Japan. *Proceedings of the Asia-Pacific Workshop on Research Coalition for Urban Earthquake Disaster Management.* Earthquake Disaster Mitigation Research Center, RIKEN, Japan: 1998: 9–17.

[17] Eguchi RT, Huyck CK, Houshmand B, Mansouri B, Shinozuka M, Yamazaki F & Matsuoka M. The Marmara earthquake: A view from space: *The Marmara, Turkey Earthquake of August 17, 1999: Reconnaissance Report*, Technical Report MCEER-00-0001. 2000: 151–169.

[18] Hasegawa H, Aoki H, Yamazaki F, Matsuoka M & Sekimoto I. Automated detection of damaged buildings using aerial HDTV images. *Proceedings of the IEEE 2000 International Geoscience and Remote Sensing Symposium.* 2000. CD-ROM.

[19] Lillesand TM & Kiefer RW. Remote sensing and image interpretation. 4th edn. Wiley. 1999.

[20] Oka S. Damages of gas facilities by Great Hanshin earthquake and restoration process. *Proceedings of the 6th US-Japan Workshop on Earthquake Disaster Prevention for Lifeline Systems.* PWRI, Ministry of Construction 1995: 253–269.

[21] Katayama T, Sato N & Saito K. SI-sensor for the identification of destructive earthquake ground motion. *Proceedings of the 9th World Conference on Earthquake Engineering* 1988: **VII**: 667–672.

[22] Shimizu Y, Watanabe A, Koganemaru K, Nakayama W & Yamazaki F. Super high-density realtime disaster mitigation system. *Proceedings of the 12th World Conference on Earthquake Engineering.* 2000. CD-ROM.

[23] Yamazaki F & Shimizu Y. Super dense real-time monitoring of earthquakes for a city gas network in Japan: *Proceedings of the 17th International Symposium on Automation and Robotics in Construction.* 2000: 581–586.

[24] Yamanouchi H & Yamazaki F. Experiments on the behavior of automobile drivers under seismic motion using driving simulator. *Proceedings of 5th US Conference on Lifeline Earthquake Engineering,* ASCE, 1999: 796–803.

[25] Maruyama Y & Yamazaki F. Dynamic response of a vehicle model with six-degrees-of freedom under seismic motion. *Structural Safety and Reliability: Proceedings of the 8th International Conference on Structural Safety and Reliability.* 2001 (to appear).

[26] Bakker E, Pacejka HB & Linder L. A new tire model with an application in vehicle dynamics studies. *Society of Automotive Engineers (SAE) Paper No. 890087,* 1989: 83–95.

Fumio Yamazaki
Institute of Industrial Science, University of Tokyo,
4-6-1 Komaba, Meguro-ku,
Tokyo 153-8505, Japan
E-mail: yamazaki@iis.u-tokyo.ac.jp