SUPER DENSE REAL-TIME MONITORING OF EARTHQUAKES FOR A CITY GAS NETWORK IN JAPAN

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Abstract: To cope with earthquake-related secondary disasters, city gas utilities in Japan have promoted several countermeasures in the last two decades. Tokyo Gas Co. introduced an earthquake monitoring and rapid damage assessment system, SIGNAL, with 331 SI-sensors in 1994, as well as installing automated shutoff valves and intelligent meters. After the 1995 Kobe Earthquake, the earthquake monitoring system is further being strengthened by introducing new SI-sensors to all the 3,700 district regulators in greater Tokyo area. A new seismic monitoring and damage assessment system named SUPREME is now under construction using the seismic information from the new SI-sensors and an enhanced GIS. This paper overviews the recent advances in the seismic safety of city gas supply systems in Japan.

Keywords: city gas network, earthquake, SI sensor, seismic monitoring, damage assessment, GIS, supply shutoff, secondary disaster.

1. INTRODUCTION

The 1995 Kobe (Great Hanshin) Earthquake caused serious damage to various infrastructures. The natural gas system in the Kobe area was also seriously affected [1, 2]. Numerous breaks in distribution and service pipes were reported. Osaka Gas stopped gas supply for 860 thousand customers in the hard-hit areas. But it took 6 to 15 hours till the decisions of supply shutoff were made because the collection of information on the extent of damage was extremely difficult just after the earthquake. Due to the massive damage to gas pipes and disruption of road networks, the service restoration took about three months.

To cope with secondary disasters, e.g., fires and explosions, after earthquakes, city gas utilities in Japan have promoted several safety countermeasures in the last decade: increasing seismic resistance of facilities and pipelines, segmentation of gas networks into blocks, earthquake monitoring by seismometers, installation of intelligent gas meters with a seismic sensor etc.

As one of such earthquake countermeasures, Tokyo Gas Co., Ltd. introduced an earthquake monitoring and rapid damage assessment system [3, 4], SIGNAL (Seismic Information Gathering and Network Alert), with 331 SI-sensors in 1994. The SI sensors [5] measure the peak ground acceleration (PGA) and spectrum intensity (SI, Fig. 1) at district regulator stations. The SI and PGA values are sent by the radio system and used for damage estimation. Together with actual damage reports, the results of the damage estimation are used for the decision-making, whether or not to shut off the gas supply.

More recently Tokyo Gas further developed new SI-sensor [6], having several new functions with the much cheaper price. The new SI-sensor can store acceleration time histories in its IC memory and send monitored strong motion indices to the Supply Control Center through public telecommunication lines. The new sensors will be installed at all the 3,700 district regulator stations within the next 7

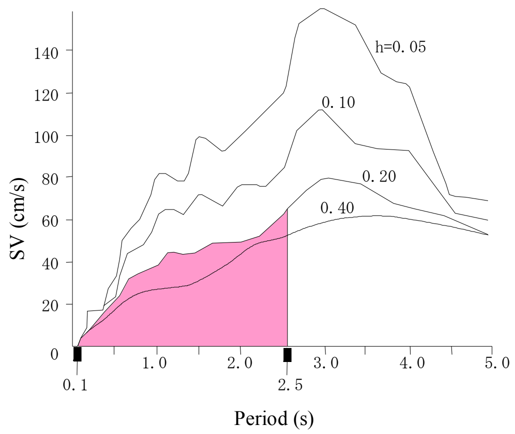


Figure 1. Definition of Spectrum Intensity: SI

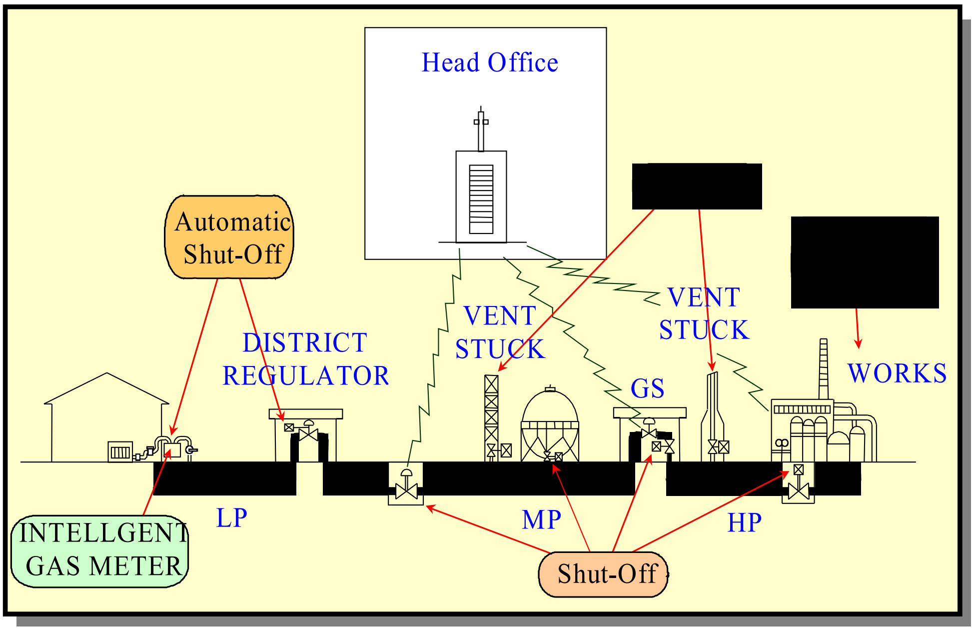


Figure 2. Emergency Shutoff Systems of Natural Gas Network of Tokyo Gas Co., Ltd.

Figure 3. Intelligent Gas Meter for Automated Shutoff under Strong Motion

years. The new SI-sensor network is named SUPREME (Super-Dense Real-time Monitoring of Earthquakes), which may be the densest seismic monitoring network in the world. The data from the network will be used for an early damage assessment of the city gas network of Tokyo Gas and the results serve as important information for the decision making of the gas supply suspension.

This paper introduces the recent advances in seismic safety of city gas systems in Japan, especially the new SI sensor and SUPREME.

2. SAFETY MEASURES OF NATRUAL GAS SUPPLY SYSTEMS IN JAPAN

Figure 2 shows emergency shutdown systems of Tokyo Gas Company with 8.7 million metered customers. The gas pressure and flow of production facilities and high-pressure (HP) pipelines are always monitored preparing for troubles. Remote-control emergency shutoff valves are equipped for primary facilities. Segmentation of gas networks is carried out in two levels: one for medium-pressure (MP) lines and another for low-pressure (LP) lines. Emergency shutoff of gas networks can be carried out for these units, called K-blocks for medium-pressure lines and L-blocks for low-pressure lines. At each customer, an intelligent gas meter (Fig. 3) stops gas supply automatically if earthquake motion larger than about 0.2 G is detected.

For low-pressure lines, emergency shutoff is carried out automatically based on measured SI values at district regulator stations. However, for medium-pressure lines, an automated shutoff system is difficult to install because the service areas and the effects of emergency shutoff are much bigger than those of low-pressure lines. It is also not easy to detect pipe breaks just after an earthquake from the changes of gas flow and pressure because pipe breaks and automated shutoffs affect conversely. Thus, a rapid damage assessment system, SIGNAL, was introduced.

The unique feature of SIGNAL is its extensive earthquake monitoring network. The monitoring system measures the PGA and SI at 331 locations in the service area by SI-sensors as shown in Fig. 4. Acceleration time histories at 5 locations and pore-water rises at 20 locations are also observed. Once an earthquake occurs, these values are sent to the supply control center of the headquarters by the company's radio network and are used in decision making of the gas supply shutoff for medium-pressure trunk lines.

The early warning system consists of hypocenter estimation and damage estimation sub-systems. For

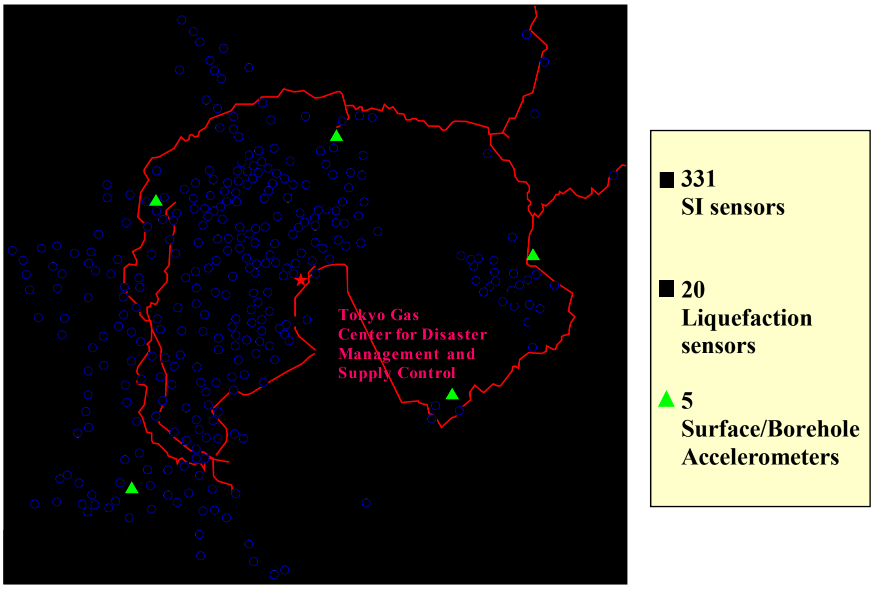


Figure 4. Seismic Monitoring Sensors of SIGNAL

the damage estimation, data on the service area, e.g. soil conditions, customers' buildings and pipelines, are stored on a workstation using GIS with pixels of 175 m×250 m. The prototype of SIGNAL was completed in 1992 and the actual system has been operating since June 1994. Information on SIGNAL and the recorded PGA and SI values from recent earthquakes are available at the homepage of Tokyo Gas (http://www.tokyo-gas.co.jp/signal).

Since seismic safety has high priority for city gas supply systems, other major gas companies in Japan also developed earthquake monitoring and rapid damage assessment systems like SIGNAL recently. Installation of the intelligent gas meters with a seismic sensor is also accelerated and almost all the customers of major gas companies have this kind of meter now.

3. DEVELOPMENT OF NEW SI SENSOR

At all the district regulators of Tokyo Gas, conventional SI sensors were deployed about ten years ago. These SI sensors have been used for automated shutoff of gas valves at the regulators by the detection of SI value of equal or greater than 30cm/s or 40cm/s. However, the conventional SI sensor cannot store acceleration time histories. In accordance with a regular replacement of the SI sensors, Tokyo Gas developed new SI sensor with much higher performance than the conventional type.

As shown in Fig. 5, the new SI sensor jointly developed by Tokyo Gas and Yamatake Co., Ltd. is very small and low-cost (1/2-1/3 compared with the conventional one) due to the adoption of an ultra small acceleration pickup (manufactured by Sumitomo Precision Products Co., Ltd.) and high

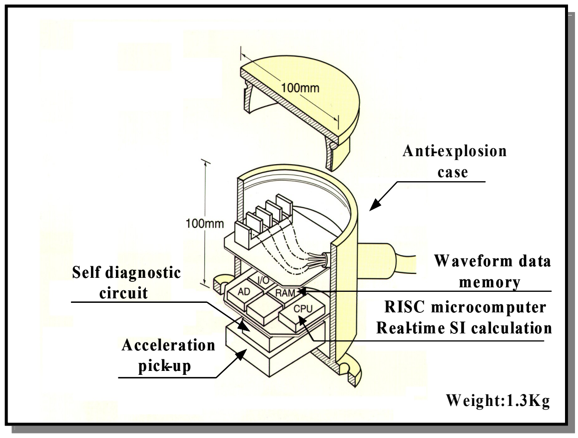


Figure 5. New SI Sensor

performance CPU and RAM devices. The new SI sensor employs a voltageless relay output for regularor shutoff, an analog output of SI value and PGA, and an alarm output for liquefaction. The analog output accommodates telemeter equipment.

The sensor is capable of measuring acceleration up to 2.0 G with precision of less than plus or minus 5 percent. The new SI sensor can store three-component accelerlation time histories in its internal memory together with header information on the occurrence time of earthquakes. The sampling rate is 1/100th of a second with a resolution of 1/8th of cm/s^2. The duration of one acceleration time history is set to be 50 seconds, centered around the motion with the largest running SI value. If a long vibration exceeding 50 seconds is detected, the time history for another 50 seconds is also stored. Six sets of time histories, listed in the order of larger SI values, can be stored in the memory.

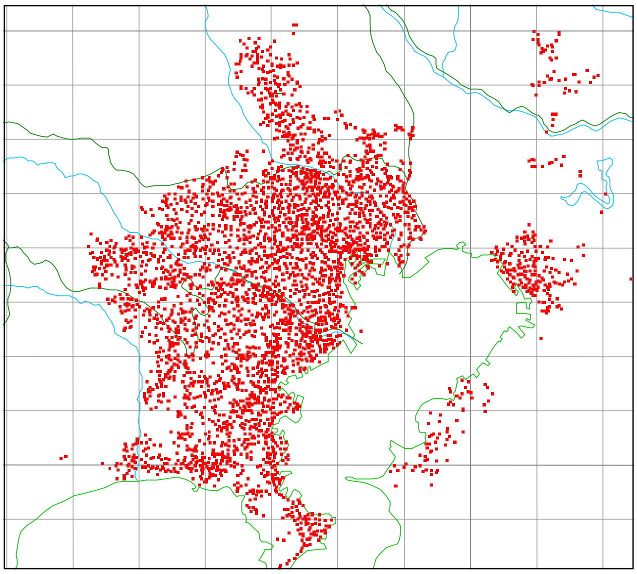


Figure 6. Location of 3,700 New SI Sensors at District Regulators for SUPREME

One of the unique features of the new SI sensor is its liquefaction detection capability. Using measured acceleration time histories, occurrence of liquefaction is estimated [6]. Studying the characteristics of the acceleration records from the liquefied sites in Japan and the United States, the following conditions were employed to judge the occurrence of liquefaction:

1) *PGA* is larger than 100 cm/s^2,
2) *SI* is larger than 20 cm/s,
3) the estimated maximum displacement *D* ($D=2SI^2/PGA$) is larger than 10 cm,
4) the estimated predominant period *T* by the zero-crossing method is larger than 2.0 seconds.

If all the above conditions are satiffied by recorded horizontal accelerations, an alarm signal of liquefaction is issured.

4. DEVELOPMENT OF NEW REAL-TIME DISASTER MITIGATION SYSTEM: SUPREME

The replacement of the exsisting SI sensors to the new SI sensors started 1997 and will end in 2007. By July 2001, the number of new SI sensors will reach 1,800. When this replacement is completed, the operational status of all the about 3,700 district regulators (Fig. 6), e.g., gas pressure and regulator shutoff/open status, can be monitored as well as SI, PGA, and liquefaction alarm. Tokyo Gas started the system design of SUPREME as an enhanced real-time earthquake monitoring and damage assessment tool. The actual operation of SUPREME is planned to start from July 2001.

If an earthquake occurs, the data from the regulators which are automatically shutoff will be sent to the supply control center by commercial telephone lines. For a large magnitude earthquake with short distance, a maximum of about one thousand regulator stations are expected to be shut-off, and even in such a case, all the data may be gathered within 20 minutes. Even the new SI sensor network for SUPREME is established, the SI sensor network with 331 new SI sensors for SIGNAL will continue to be in operation. The seismic information (SI and PGA) from these instruments is much faster (within about 10 minutes) because the company's radio system is used for the collection of these data.

Figure 7 depicts the planned communication network of SUPREME. The remote monitoring units in SUPREME employ the public telephone lines and they are used to monitor the pressure guages and gas leak detectors even in the ordinary time. Heavy traffic congestion is expected in the telecommunication lines, especially in case of large earthquakes. A newly developed remote monitoring system (Disaster Mitigation DCX) incorporates a function that enables it to assemble and transmit the alarms to reduce a number of dialings.

5. GIS DATA AND SEISMIC ZONING OF SUPREME

Since the number of seismometers in SUPREME will be much larger than that in SIGNAL, more detailed GIS data and seismic zoning are desirable. A new geological classification shown in Fig. 8 (a) was developed as a base map of seismic zoning.

Furthermore, a new site amplification map shown in Fig. 8 (b) was developed in order to estimate the spatial distributiuon of SI value based on observed SI values from the new SI sensors. This map was made by the following steps: 1) Utilizing a total of about 50,000 borehole logging data (SPT N-values), the shear wave velocities of surface layers at the boring

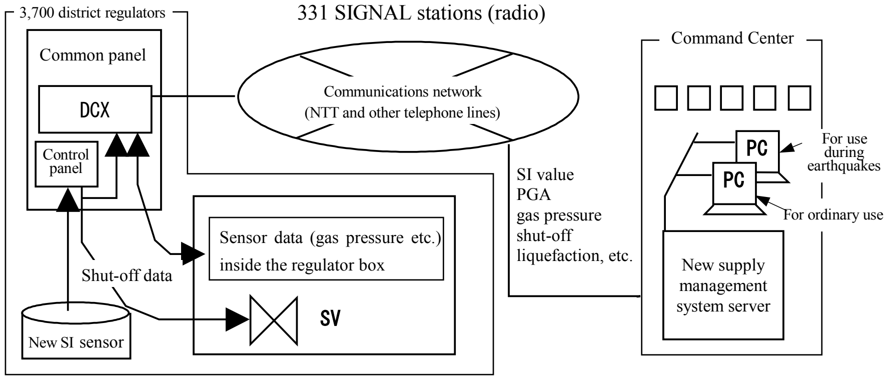
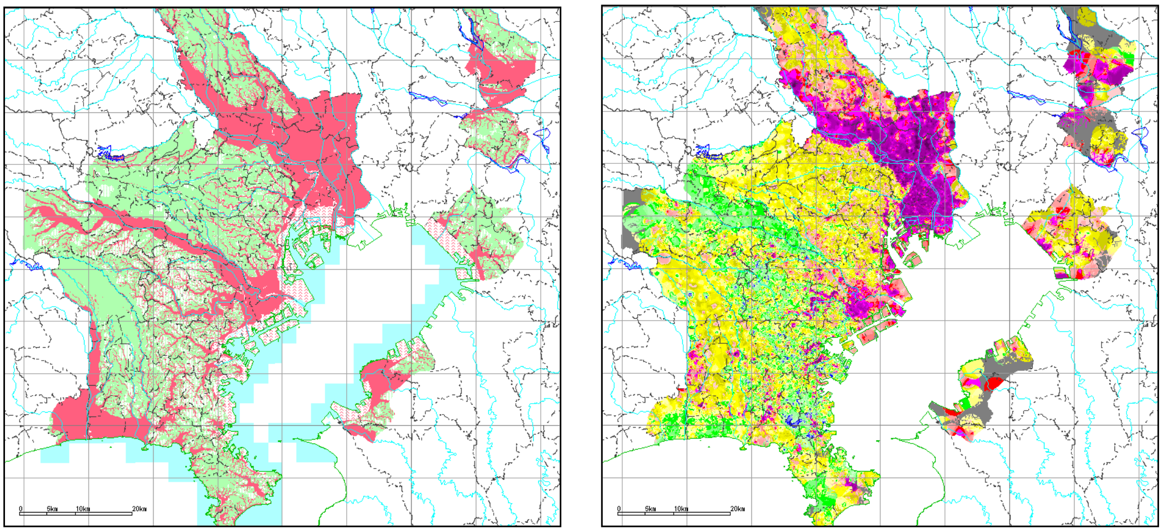


Figure 7. System Configuration of SUPREME



(a) Geological Classification (b) Estimated Site Amplification Ratio of SI

Figure 8. GIS Maps Employed in SUPREME

points are estimated; 2) the site amplification factors for SI values are estimated at the boring points using the relationship between the avarage shear wave velocity (AVS) and the amplification factor [7], developed based on K-NET records; 3) the spatial distribution of site amplification factor is estimated based on a weighted avarage of the amplification factors of surrounding boring points [8].

To estimate the spatial variation of SI value from observed SI values from the new SI sensors, a weighted avarage scheme is again employed for the normalized SI values (converted to the outcrop base of V_s=600m/s utilizing the amplification factor). The predicted surface SI distribution with 50m x 50 m mesh is utilized to estimate seismic damage to buried pipes and customers' buildings.

7. SI SENSOR NETWORK IN TAIPEI BASIN AND ITS PERFORMANCE IN THE 1999 CHI-CHI EARTHQUAKE

The Great Taipei Gas Co., Ltd., Taiwan's largest gas utility with 330,000 customers, introduced the new SI sensors to all the 31 regulator stations in 1999. These SI sensors were set to shut off the gas supply automatically if the SI value exceeds 40cm/s.

Soon after the installation of the SI sensors, the Chi-Chi Earthquake with M_w=7.6 occurred in the central part of Taiwan on September 21, 1999. The epicenter is located about 160km southwest of Taipei and only limited damage was reported in Taipei, except one collapsed builiding.

In the main shock of the event, 16 SI sensors recorded the strong motion successfully [9] as shown in Fig. 9. Since the largest SI was 27.4cm/s (PGA=139.6cm/s^2) at Shazoo station, no shutoff was occurred in the gas supply. The smallest recorded SI was 8.3cm/s (PGA=38.0cm/s^2) at Yenson station, within 2km from Shazoo station. Yenson is located on hard rock while Shazoo is on weak offshore deposits. The distribution of SI and PGA indicates that the soil condition significantly affects the site

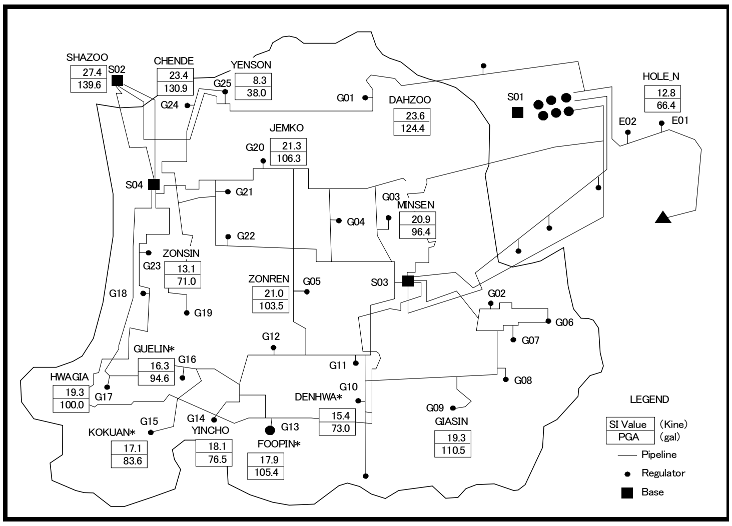


Figure 9. Distribution of SI and PGA in Taipei Observed by New SI Senors in the 1999 Chi-Chi Earthquake

amplification factor. To investigate the site response characteristics in more detail, microtremor observation was also carried out at all the SI sensor stations. The results of these investigations may provide useful information for the site amplification and seismic zoning of Taipei.

8. CONCLUSIONS

In this paper, the recent developments in seismic safety of natural gas systems in Japan was described. To cope with earthquake-related secondary disasters, city gas utilities in Japan have promoted several countermeasures in the last two decades. Tokyo Gas Co., Ltd. introduced an earthquake monitoring and rapid damage assessment system SIGNAL with 331 SI-sensors as well as installing automated shutoff valves and intelligent meters. After the 1995 Kobe Earthquake, the earthquake monitoring system is further being strengthened by introducing newly developed SI-sensors to all the district regulators. A new seismic monitoring and damage assessment system SUPREME is now under development using an enhanced telecommunication network and GIS. The performance of the new SI sensors installed in Taipei during the 1999 Chi-Chi earthquake was also reported.

REFERENCES

[1] Oka, S., "Damages of Gas Facilities by Great Hanshin Earthquake and Restoration Process.", *Proc. of the 6th U.S.-Japan Workshop on Earthquake Disaster Prevention for Lifeline Systems*, pp. 253-269, PWRI, Ministry of Construction, 1995.

[2] Yamazaki, F. and Tong, H., "Damage and Restoration of Natural Gas System in the 1995 Kobe Earthquake"*, The 1995 Hyogoken-Nanbu Earthquake -Investigation into Damage to Civil Engineering Structures-*, JSCE, pp. 219-227, 1996.

[3] Yamazaki, F., Katayama, T. and Yoshikawa, Y.," On-Line Damage Assessment of City Gas Networks Based on Dense Earthquake Monitoring", *Proc. of 5th U.S. National Conference on Earthquake Engineering*, Vol. 4, pp. 829-837, 1994.

[4] Yoshikawa, Y., Kano, H., Yamazaki, F., Katayama, T. and Akasaka, N., "Development of SIGNAL: An Early Warning System of City Gas Network", *Proc. of 4th U.S. Conference on Lifeline Earthquake Engineering*, pp. 160-167, ASCE, 1995.

[5] Katayama, T., Sato, N., and Saito, K. "SI-sensor for the Identification of Destructive Earthquake Ground Motion", *Proc. of the 9th World Conference on Earthquake Engineering*, VII, pp. 667-672, 1998.

[6] Shimizu, Y., Watanabe, A., Koganemaru, K., Nakayama, W. and Yamazaki, F., "Super High-Density Realtime Disaster Mitigation System, *12th World Conference on Earthquake Engineering,* CD-ROM, 7p, 2000.

[7] Tamura, I., Yamazaki, F., and Shabestari, K. T., "Relationship Between the Average S-Wave Velocity and Site Amplification Ratio Using K-NET Records", *Proceedings of the 6th International Conference on Seismic Zonation,* 2000 (to appear).

[8] Shimizu, Y., Ishida, E., Isoyama, R., Koganemaru, K., Nakayama, W., and Yamazaki, F., "Development of Super High-Density Realtime Disaster Mitigation System for Gas Supply System", *Proceedings of the 6th International Conference on Seismic Zonation,* 2000 (to appear).

[9] Shimizu, Y., Koganemaru, K Yamazaki, F., Tamura, I., and Suetomi, I., "Seismic Motion Observed in Taipei Basin by New SI sensors and Its Implication to Seismic Zoning", *Proceedings of the 6th International Conference on Seismic Zonation,* 2000 (to appear).