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SUPER DENSE SEISMIC MONITORING AND EARLY DAMAGE ASSESSMENT FOR A CITY GAS NETWORK IN JAPAN

Fumio Yamazaki[1], Yoshihisa Shimizu[2], Wataru Nakayama[2], Ken'ich Koganemaru[2],
Eisuke Ishida[3], Ryoji Isoyama[3]

ABSTRACT : To cope with earthquake-related secondary disasters, city gas utilities in Japan have promoted several countermeasures in the last two decades. Tokyo Gas Company 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.

1. INTRODUCTION

The 1995 Kobe (Hyogoken-Nanbu) earthquake caused serious damage to various in-frastructures and buildings in the highly populated area of central-western Japan. The natural gas system in the Kobe area was also seriously affected [1]. Numerous breaks in distribution and service pipes were reported. Osaka Gas Company 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 since the collection of information on the extent of damage was extremely difficult due to heavy congestion in telephone and road traffics just after the earthquake. The service restoration took about three months because of the massive damages to gas pipes and disruptions of road networks.

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 [2], SIGNAL (Seismic Information Gathering and Network Alert), with 331 SI-sensors in 1994. The SI sensors [3] measure the peak ground acceleration (PGA) and spectrum intensity (SI) at district regulator stations. Note that the spectrum intensity is the averaged velocity response spectrum with 20 % damping over the structural period between 0.1 s and 2.5 s. In SIGNAL, 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.

[1] Institute of Industrial Science, University of Tokyo, Japan, Ph. D.
[2] The Center for Supply Control and Disaster Management, Tokyo Gas Co., Ltd., Japan, Ph. D.
[3] Japan Engineering Consultants Co. Ltd., Japan, Ph. D.

More recently Tokyo Gas further developed new SI-sensor [4], having several new functions with a 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 6 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 natural gas systems in Japan.

2. SAFETY MEASURES OF NATRUAL GAS SUPPLY SYSTEMS IN JAPAN

Figure 1 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 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 seismic monitoring network. The monitoring system measures the PGA and SI at 331 locations in the service area by SI-sensors as shown in Fig. 2 (a). 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 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 175m x 250m. 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).

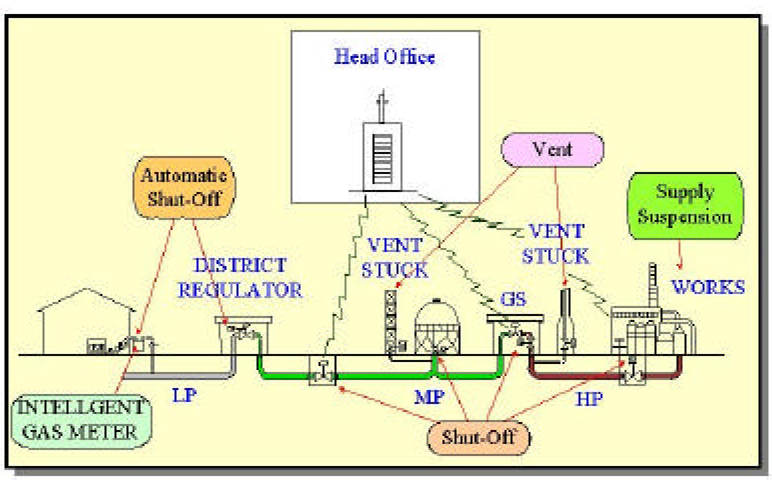


Figure 1. Emergency shutoff systems of natural gas network of Tokyo Gas Co., Ltd.

3. DEVELOPMENT OF NEW SI SENSOR

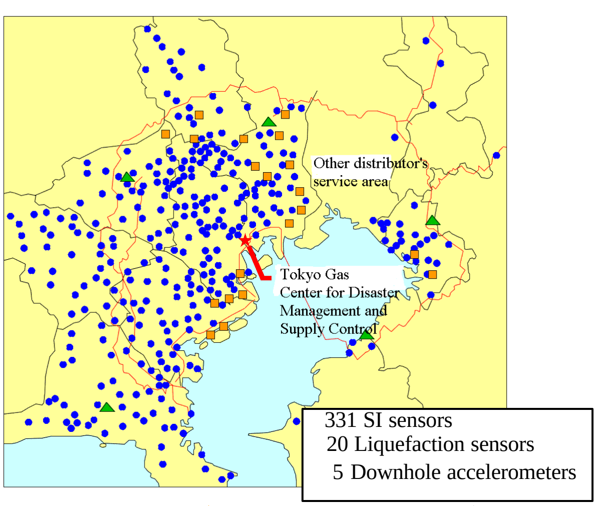
At all the district regulators of Tokyo Gas, conventional SI sensors were deployed about ten years ago. These SI sensors have been used for automated shutoff of gas valves at the regulators by the detection of SI value of equal or greater than 30cm/s or 40cm/s. However, the conventional SI sensor cannot store acceleration time histories. In accordance with a regular replacement of the SI sensors for every ten years, Tokyo Gas developed new SI sensor (Fig. 3) with higher performance than the conventional type.

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 performance CPU and RAM devices. The new SI sensor employs a voltage-less relay output for regulator 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%. The new SI sensor can store three-component acceleration 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.

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 [4]. 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 s. If all these conditions are satisfied by recorded horizontal accelerations, an alarm signal of liquefaction is issued.

4. NEW REAL-TIME DISASTER MITIGATION SYSTEM: SUPREME

The replacement of the existing 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. 2(b)), 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.



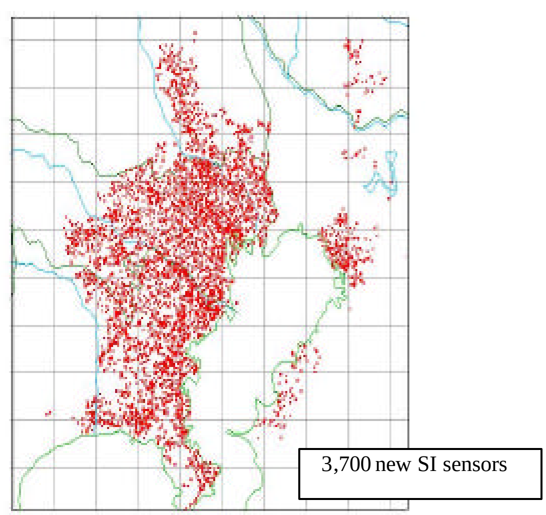


Figure 2. Distribution of seismic sensors in (a) SIGNAL (left) and (b) SUPREME (right)

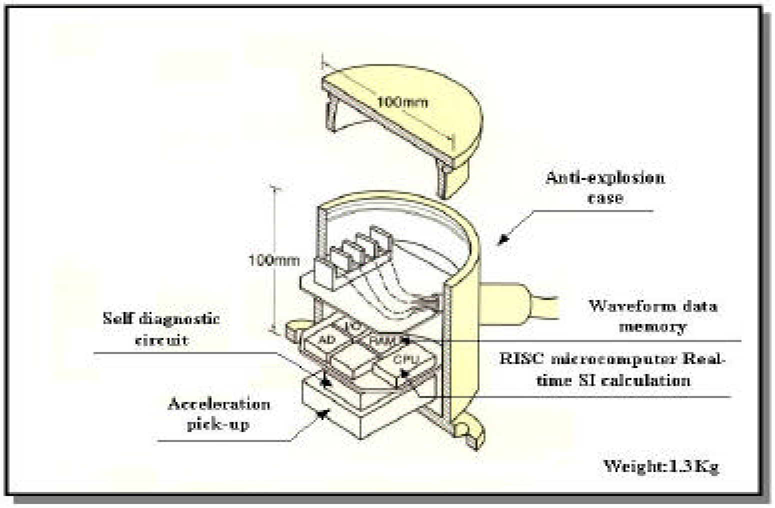


Figure 3. New SI sensor

If an earthquake occurs, the data from the regulators which are automatically shut off 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 after 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.

The remote monitoring units in SUPREME employ the public telephone lines and they are used to monitor the pressure gauges and gas leak detectors even in ordinary time. Heavy traffic congestion is expected in the telecommunication lines 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 dialing.

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. 4 (a) was developed as a base map of seismic zoning. Furthermore, a new site amplification map shown in Fig. 4 (b) was developed in order to estimate the spatial distribution 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 points are estimated;
2) the site amplification factors for SI values are estimated at the boring points using the relationship between the average shear wave velocity (*AVS*) and the amplification factor [5], developed based on K-NET [6] records;
3) the spatial distribution of site amplification factor is estimated based on a weighted average of the amplification factors of surrounding boring points [7].

To estimate the spatial variation of SI value from observed SI values by the new SI sensors, a weighted average 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.

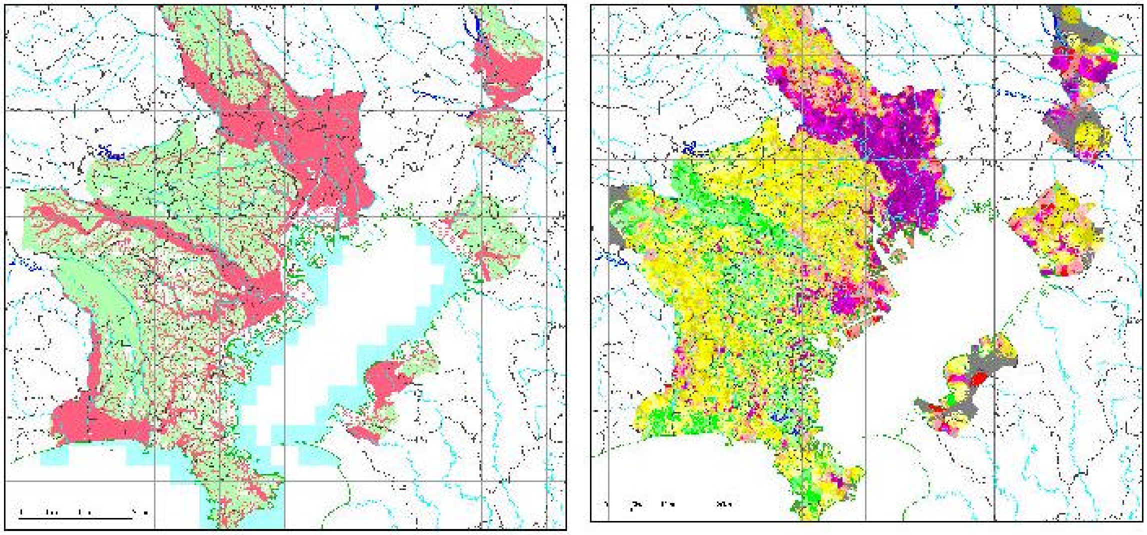


Figure 4. GIS maps employed in SUPREME. Geological classification (left) and estimated site amplification ratio of SI (right)

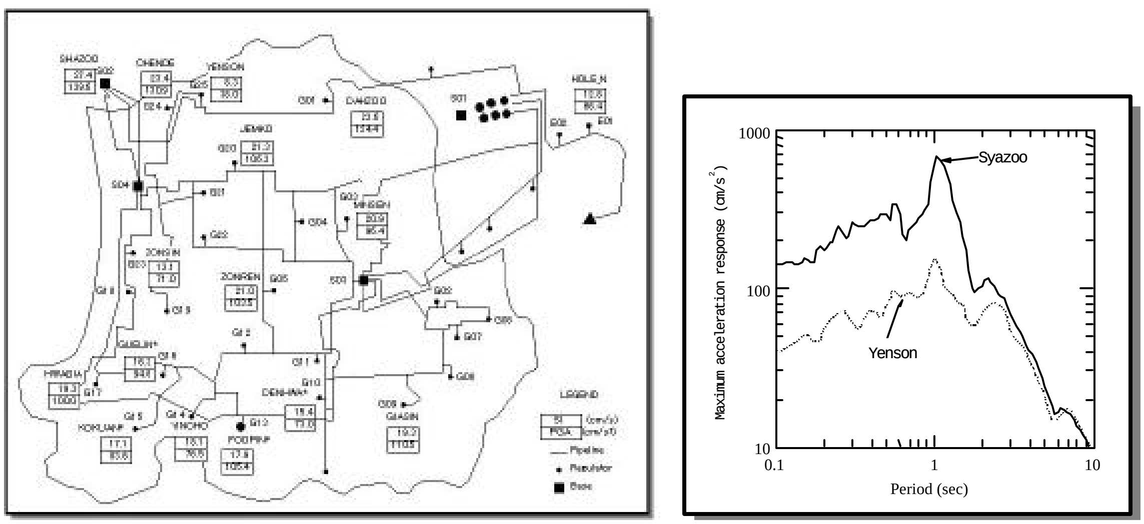


Figure 5. Distribution of SI and PGA in Taipei observed by new SI sensors in the 1999 Chi-Chi earthquake (left) and the 5% damped acceleration response spectra for the records at Shazoo and Yenson stations (right)

6. 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 for one collapsed building.

In the main shock of the event, 16 SI sensors recorded the strong motion successfully [7] as shown in Fig. 5. 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 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.

7. CONCLUSIONS

The recent developments in seismic safety of natural gas systems in Japan were presented. To cope with earthquake-related secondary disasters, city gas utilities in Japan have promoted several countermeasures in the last two decades. Tokyo Gas Company 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 3,700 district regulators. The spectrum intensity and peak ground acceleration values are observed in real-time by these sensors and they are used as indices to predict damage to the natural gas supply system. A new seismic monitoring and damage assessment system SUPREME is now under development using an enhanced telecommunication network and GIS. The system is expected to play an important roll to sustain urban safety even in case of destructive earthquakes. The performance of the new SI sensors installed in Taipei during the 1999 Chi-Chi earthquake was also reported.

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