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DEVELOPMENT OF SUPER HIGH-DENSITY REALTIME DISASTER MITIGATION SYSTEM FOR GAS SUPPLY NETWORKS

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ABSTRACT
Tokyo Gas Company has developed its super high-density real-time disaster mitigation system "SUPREME" for gas supply networkss, to cope with earthquake related secondary disasters. SUPREME has been in operation since July 2001, using new SI sensors to be installed at all the 3,700 district regulators in greater Tokyo area. Immediately after the occurrence of an earthquake, seismic data from the new SI sensors are relayed to the main system where precise estimates of the damage to gas pipes and customers' buildings are made using an enhanced GIS. Moreover, all the regulators can be shut off either automatically on site or remotely from SUPREME during earthquakes to prevent secondary disasters caused by gas leaks. This paper introduces the recent advances in seismic safety of city gas supply systems in Japan.

Keywords: City gas network; Earthquake; SI sensor; Seismic monitoring; GIS; Damage assessment; Supply shutoff

INTRODUCTION
The 1995 Kobe (Great Hanshin, Hyogoken-Nanbu) earthquake caused serious damage to various infrastructures and buildings in the highly populated area of central-western Japan. 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 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 because the collection of information on the extent of damage was extremely difficult because of heavy congestion in telephone and road traffics just after the earthquake. Due to the massive damages to gas pipes and disruptions of road networks, the service restoration took about three months.

To cope with secondary disasters, e.g., fires and explosions, following 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 332 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 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 4 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. Moreover, in SUPREME, gas supply can be shut off at all the district regulator stations in a damaging earthquake, either automatically on site or by remote control from the control center. Then, even in a damaging earthquake, safety will be secured quickly for heavily damaged areas.

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

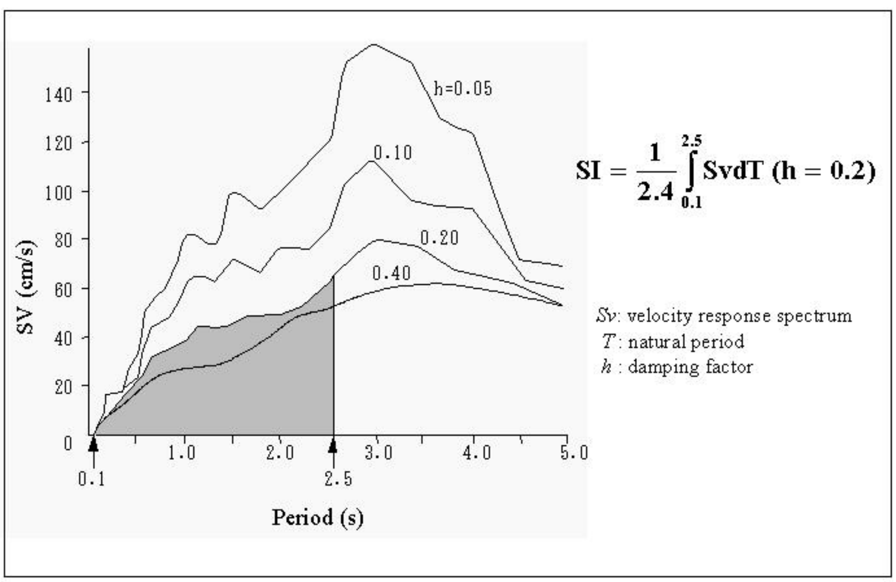

Figure 1: Definition of spectrum intensity SI.

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 with much higher performance than the conventional type.

As shown in Fig. 2, 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 a ultra small acceleration pickup 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 percent. 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. The duration of one acceleration time history is set to be 120 seconds, centered at the motion with the largest running SI value. If a long vibration exceeding 120 seconds is detected, the time history for another 120 seconds is also stored. Ten sets of time histories, listed in the order of larger SI values, can be stored in the memory.

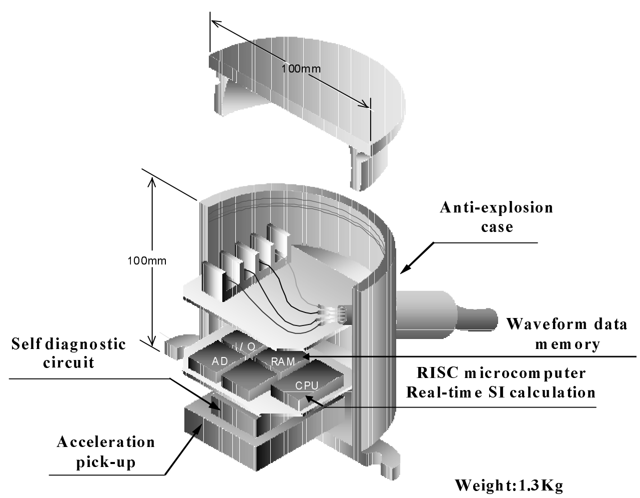

Figure 2: New SI sensor.

One of the unique features of the new SI sensor is its liquefaction detection capability. Using measured acceleration time histories, the 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 satisfied by horizontal acceleration records, an alarm signal of liquefaction is issued.

NEW 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. 3. 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.

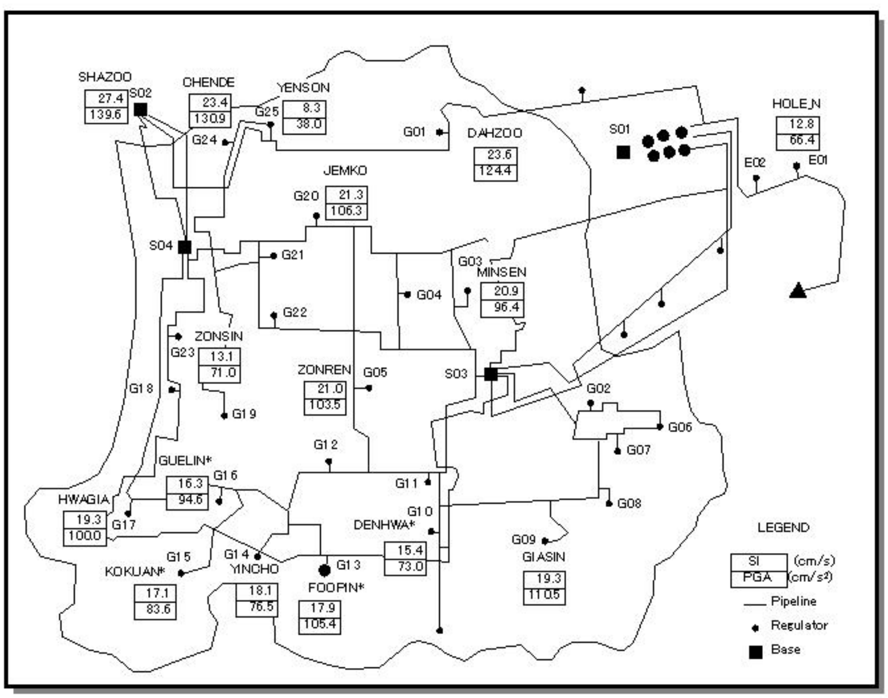

Figure 3: Distribution of SI and PGA in Taipei observed by new SI sensors in the 1999 Chi-Chi earthquake.

DEVELOPMENT OF NEW REAL-TIME DISASTER MITIGATION SYSTEM: SUPREME

The installation of new SI sensors started 1997 and will end in 2006. By March 2002, the number of new SI sensors will reach 1,800. When this installation is completed, the operational status of all the about 3,700 district regulators (Fig. 4), e.g., gas pressure and regulator shutoff/open status, can be monitored as well as SI, PGA, and liquefaction alarm. In addition, the district regulators can be shut off remotely. Tokyo Gas started the system design of SUPREME as an enhanced real-time earthquake monitoring, damage assessment and damage mitigation tool. The actual operation of SUPREME started in July 2001.

If an earthquake occurs, the data from the regulators that 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 3,700 new SI sensor network for SUPREME is established, the 332 new SI sensor network for SIGNAL continues to be in operation. The SI and PGA values from these instruments are much faster (within about 10 minutes) because the company's radio system is used for the collection of these data.

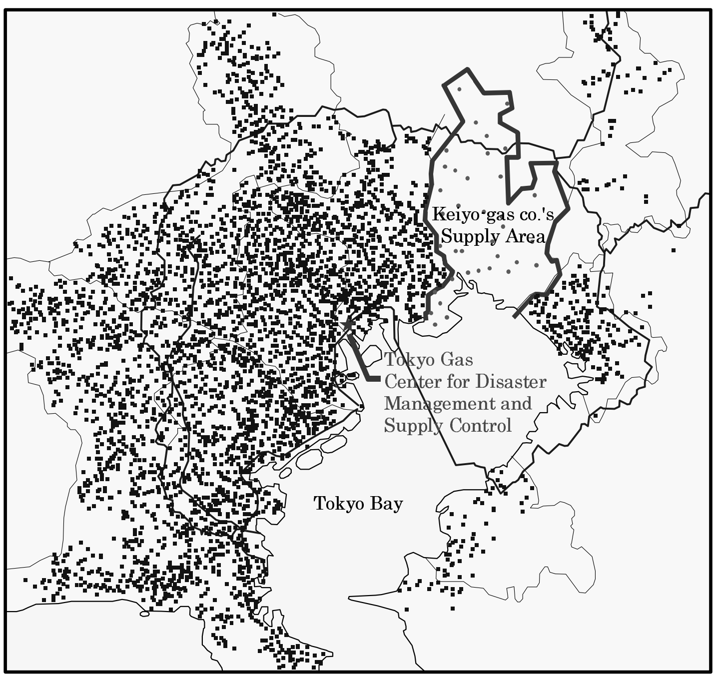

Figure 4: Location of 3,700 new SI sensors at district regulators for SUPREME.

Figure 5 depicts the communication network of SUPREME. 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 an 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. Moreover, all these public lines are designated as prioritized ones by telecommunication companies, in which less congestion can be expected.

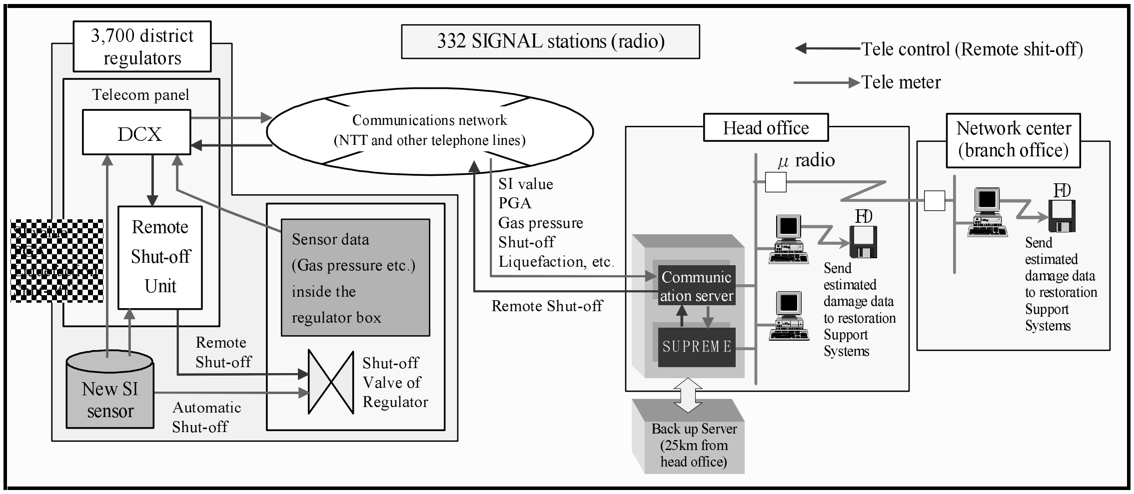

Figure 5: System configuration of SUPREME.

REMOTE REGULATOR SHUT OFF FUNCTION OF SUPREME

If a large-scale earthquake occurs in the greater Tokyo area, low-pressure gas pipelines will be heavily damaged. Therefore, an immediate gas supply shut-off is necessary in hard-hit areas to prevent secondary disasters, caused by gas leakage from broken pipes. Automated shut-off devices are now installed at all the district regulators for this purpose but it is not sufficient. Because of the difference in soil amplification, ground motion will vary at each regulator site. Then, it may happen that some regulators are shut off but others are still working. Since low-pressure gas pipes are densely deployed and linked to neighboring regulators, gas supply will continue if some working regulators exist nearby. In other words, gas leakage cannot be stopped. In such a case, company staff will be dispatched to the site to close working regulators manually. However, in a big earthquake, because of traffic congestion and road damages, such work is quite difficult and time consuming.

The countermeasure for this problem is “shutoff by remote control”. Here, the conventional remote control system, which is commonly employed for high-pressure pipeline systems, uses company’s radio communication or dedicated lines with redundancy to keep high reliability. But this system is not suitable for 3,700 district regulator stations in SUPREME, due to its high cost. Public lines have already been installed at all the stations but they are not appropriate for remote shut-off in terms of security, because anyone who knows the telephone number can easily shut off the regulator. Hence a remote shut-off unit was developed to achieve high reliability and security for remote control of regulators even in case public lines are used

The remote shut-off unit is installed at each regulator station as shown in Fig.5 to accept the remote shut-off command from SUPREME Host only for a short time (6 hours) just after the occurrence of an earthquake, to prevent hacker’s attack in an ordinary time. It has the so-called “GATE”, which is normally closed but opens only when ground shaking is measured by both a new SI sensor and a mechanical starter to accept the command through the DCX using public lines. The opening trigger is set as 10 cm/s for the new SI sensor and 50 cm/s^2 for the mechanical starter, as shown in Fig.6. The installation cost of the remote shut-off unit is only 1/40 compared with conventional systems.

1,800 remote shut-off units have been installed so far, and the number will be increased to 3,700 by 2006. Then, besides automatic shut-off by new SI sensor at each regulator station, remote shut-off can be conducted for the surrounding area of the automatically shut-off regulator from the SUPREME Host to realize immediate low-pressure gas supply suspension. Here, simulation was carried out to compare the required time for full low-pressure gas supply shut-off between using the automated shut-off system plus manual shut-off and using the automated shut-off system plus the remote shut-off from SUPREME. The potential risk of secondary disasters, shown as the shaded area in Fig.7, was compared between the two cases. Note that we defined the potential risk of secondary disasters as follows:

$$\text{The potential risk of secondary disasters} = \sum_{i=1}^{N} t_i$$

where N is the total number of regulators to be shut-off and t_i is the time required to shut off regulator i.

The simulation was conducted under the assumption that the probable biggest earthquake occurred in the greater Tokyo area. As shown in Fig.7, the number of regulator to be shut off is 1,200. Immediately after the occurrence of the earthquake, 850 out of 1,200 regulators were shut off automatically by new SI sensors which detect strong shaking more than the set-value (SI = 30 or 40 cm/s), but 350 regulators remained still working. If remote shut-off can be made by SUPREME, most of them would be closed in 1 hour. The result of simulation with the assumption that 5% of public lines were damaged shows that it requires 3.5 hours for the complete shut-off because company staffs need to go to the sites where public lines are damaged to close the regulators manually. On the other hand, if there is no remote shut-off system, it requires as much as 39 hours for the complete shut-off, due to probable traffic congestion and road damages.

The significant difference is seen in the potential risk between the two cases as shown in Table 1. The potential risk can be reduced to only 3% if the remote shut-off function in SUPREME is introduced.

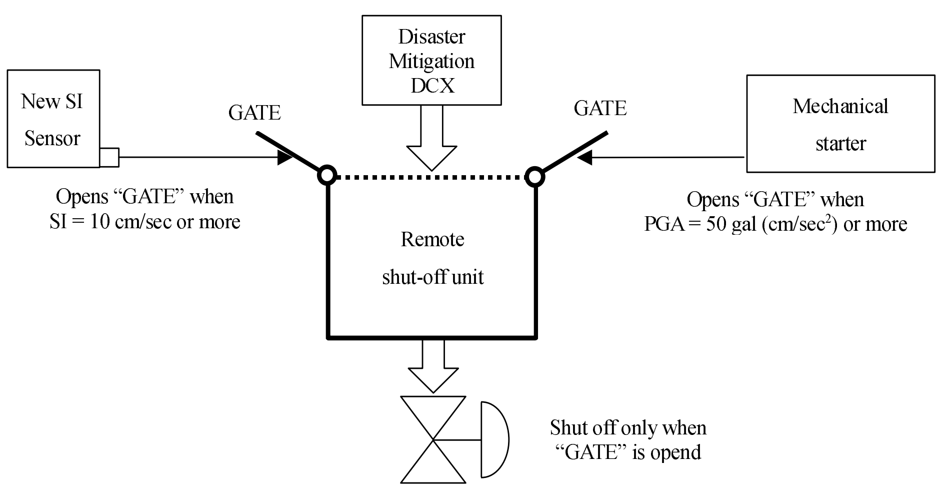

Figure 6: Mechanism of the remote shut-off unit

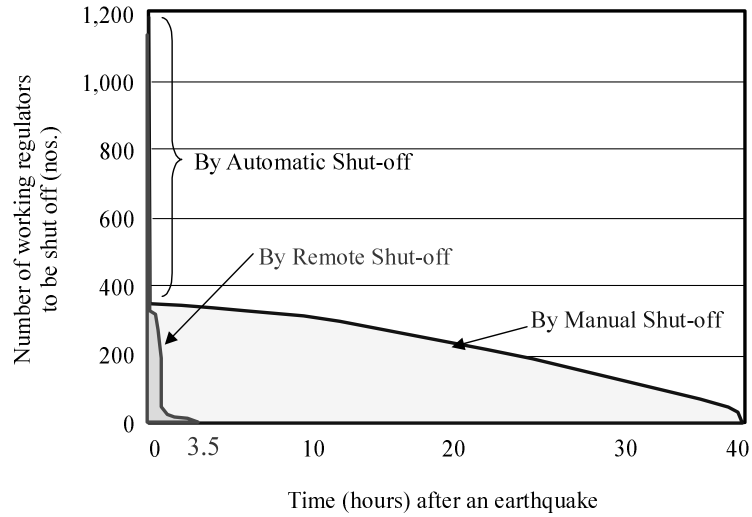

Figure 7: Comparison of elapsed time to shut-off regulators between the two cases after the occurrence of the scenario earthquake

Table 1: Comparison of the elapse time of supply shut-off and the potential risk between the two cases

Case	Time required for completion of shut-off	The ratio of potential risk
Automatic shut-off + Manual shut-off	39 hours	1.0
Automatic shut-off + Remote shut-off	3.5 hours	0.03

GIS DATA AND SEISMIC ZONING OF SUPREME

Since the number of seismometers in SUPREME is much larger than that in SIGNAL, more detailed GIS data and seismic zoning are desirable. A new geological classification map shown in Fig. 8 (a) was developed as a base map of seismic zoning. The digital map was made using a raster GIS with 50m x 50 m pixel size, considering the topography and subsurface geology of the greater Tokyo

Furthermore, a new site amplification map shown in Fig. 8 (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 60,000 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 [8], developed based on K-NET [9] records;

3) the spatial distribution of site amplification factor is estimated based on a weighted average of the amplification factors of surrounding boring points [10].

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 on 50m x 50 m mesh is utilized to estimate seismic damage to buried pipes and customers' buildings. This result will be used as strong supportive information for the supply control center to make a decision of emergency response.

(a) Geological classification (b) Estimated site amplification ratio of SI

Figure 8: GIS maps employed in SUPREME system.

CONCLUSIONS

In this paper, a new seismic monitoring, damage assessment and damage mitigation system, SUPREME, for city gas supply networks in the greater Tokyo area was introduced. SUPREME has been developed and is now in operation with newly deployed new SI sensors. The new SI sensor is a type of seismometer measuring acceleration and calculating the spectrum intensity (SI), which is the index used for the measure of gas supply suspension in Japan. The number of new SI sensors is 1,800 as of March 2002 and will be 3,700 in 2006. Immediately after the occurrence of an earthquake, seismic data from the new SI sensors are relayed to the main system, where precise estimates of the damage to gas pipes and customers' buildings are made on an enhanced GIS. Moreover, all the regulators can be shut off either automatically on site or by remote control from SUPREME to prevent secondary disasters caused by gas leaks. The system is expected to play an important roll to sustain urban safety even in case of destructive earthquakes.

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