Development of Real-Time Safety Control System for Urban Gas Supply Network

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Abstract: The seismic safety of city gas supply has been the major research topic of the writers in past decades. To avoid earthquake hazards due to leakage of gas from breakage of buried pipes, a real-time safety control system, *SUPREME*, has been deployed and put into practical use. *SUPREME* employs 3,800 new spectrum intensity sensors and remote control devices to achieve quick gas supply shut off. It monitors the earthquake motion at a large number of sites on a real-time basis, interprets the data, and assesses gas pipe damage in order to decide whether or not the gas supply should be interrupted. The present paper first describes the philosophy behind this system. Second, it describes the performance of the system during the recent Taiwan earthquakes as well as more significant design earthquakes. This system represents the state-of-the-art of computer-operated safety measures, achieved by advanced geotechnical engineering.

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Introduction

Urban gas supply is an important source of energy, and supports many aspects of our daily lives. In comparison with other energy sources, gas is more vulnerable to earthquake risk. Since it is flammable, leakage due to damages in pipes or other facilities may lead to significant fires and, in the worst case, explosions. After the Kobe earthquake in 1995, for example, 8 fires out of a total of 175 were related to leakage of gas and malfunctioning of gas facilities (Japan Firefighters Association 1996). O'Rourke and Palmer (1994) made similar points concerning the 1994 Northridge earthquake. The conventional emergency measure to cope with such hazards has been to shut down the gas supply. In case of the 1995 Kobe earthquake, approximately 859,000 shut downs were required, needing 85 days for the ultimate recovery (Agency of Natural Resources of Energy 1996). Another important problem was that it took as long as 15 h to put the shut down in effect. To avoid such a delay, it is essential to collect information quickly about the situation of gas supply network. Consequently, efforts were initiated after the Kobe earthquake to develop a real-time system to mitigate earthquake-induced damage in gas supply networks. The aim was to develop a system that collected information quickly, and, if necessary, carried out emergency measures.

Tokyo Gas has understood the need of a real-time system since the 1980s. The first version of such a system was named *SIGNAL* (Yamazaki et al. 1995), which went into service in June 1994, seven months prior to the Kobe earthquake. The *SIGNAL* system consisted of seismic monitoring sensors deployed over the gas supply service area and connected to headquarters by communication channels. Those sensors included 332 transducers of spectrum intensity (SI), 20 liquefaction sensors and 5 seismographs embedded in hard base layers.

To achieve further reliability, a new miniature seismograph was developed. Named the "New SI Sensor," this device houses an electronic circuit, which determines the SI value more precisely, detects the onset of liquefaction, and transmits the time history of seismic acceleration to headquarters for more detailed interpretation. Consequently, a new safety system called *SUPREME* (super-dense realtime monitoring of earthquakes) was developed, which employs 3,800 of the new SI sensors. The present text introduces this new system.

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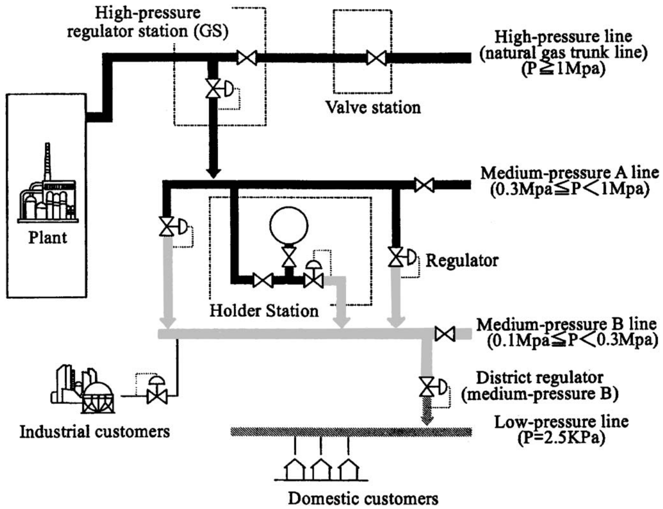

Fig. 1. Schematic diagram of pipeline network of Tokyo Gas Company

Seismic Safety Measure in Urban Gas Industry

The *SUPREME* system is always supported by conventional safety measures. In this respect, it is very important to introduce here the basic structure of the seismic safety measures utilized by Tokyo Gas.

This utility has a service area of 3,100 km^2 in and around Tokyo where there are 9.6 million customers (as of March 2005). Fig. 1 illustrates the structure of the gas supply network, in which pipelines are classified into four groups. The high-pressure pipeline has 700 km in length with a gas pressure of 1 MPa or higher. Valve stations are intended to stop gas flow in this pipeline if necessary. Second, the pipelines with medium pressure are further classified into two groups: Group A with pressure of 0.3–1.0 MPa and Group B with 0.1–0.3 MPa. They are of 2,400 and 3,600 km in length. The service pipelines have low pressure of 2.5 kPa and measure 44,100 km in total. "Regulators" in Fig. 1 are facilities for lowering the gas pressure, and there are 3,800 district regulators reducing the pressure from the medium level to the service pipeline level.

Efforts to enhance seismic safety have traditionally been focused on the major pipelines with high and medium pressure. The basic philosophy has been that gas facilities should maintain their serviceability without damage during strong earthquakes by employing high standards of seismic safety through design, materials, installation, reinforcement if necessary, and adequate maintenance. The state of gas flowing in these trunk pipes is tele-monitored 24 h a day, and in emergencies officers can stop the gas supply by closing valves remotely by wireless. The specification for this communication is such as 9,600 bit per second through 400 MHz band. For further safety, vent stacks are controlled by wireless as well, and are used to remove gas from the pipes.

In contrast, pipes with lower pressure are prone to earthquake hazards. In particular during the Kobe earthquake, there were 21,000 reports of damage such as leakage and restoration due to ground shaking, liquefaction, ground deformation, etc. Although improvement of seismic resistance in small pipes would be desirable, it has not been a practical solution to date due to the following reasons:

- The total length of pipeline is too large for any immediate action to be taken; and
- Pipes on customers' land are customers' property, which the gas company cannot control.

Consequently, pipelines with low pressure are expected to suffer many leakage problems when a big earthquake occurs. To avoid problems, it is reasonable to stop the gas supply automatically by sensing the intensity of earthquake motion.

The idea of safety in low-pressure pipes is made real by two devices. The first one is a district regulator, which normally has the role of reducing the level of gas pressure from medium to low. This facility is equipped with an SI sensor that monitors the seismic spectrum intensity, SI, which was originally proposed by Housner (1961) and takes a value similar to the maximum velocity of ground motion (Towhata et al. 1996)

$$SI = \frac{1}{2.4}\int_{0.1}^{2.5} SV(20\%\ \text{critical damping ratio})dT \qquad (1)$$

where SV=relative velocity response spectrum of the observed earthquake motion at a natural period of T. Note that the averaging is made for T from 0.1 to 2.5 s. Details of an SI sensor are presented in Appendix I as well as in Koganemaru et al. (2000). SI is chosen because Tokyo Gas experience shows that maximum acceleration exceeding 300 gal does not necessarily cause damage to embedded pipeline networks. The maximum ground velocity may be as appropriate as SI, but SI is preferred here because it takes into account the response of structures in general.

At present, a district regulator stops the gas supply if SI value exceeds 30–40 cm/s. The other gas supply stopper is a microcomputer-operated "intelligent meter." This device is installed at the connection to all individual customers' sites and automatically stops the gas supply if seismic acceleration greater than 200 cm/s^2 is sensed. The newly introduced *SUPREME* system functions in the context of these existing achievements.

Improvement of Seismic Safety Measures after 1995

Until the 1995 Kobe earthquake, the safety measures supposed that the number of shut-down clients would be of the order of 200,000, which was the case during the 1978 Miyagi-Ken-Oki earthquake. Accordingly, the extent of emergency action required was not expected to be very large. The experience of the Kobe earthquake, however, indicated clearly that the previous assessment was totally wrong. In the Tokyo area where the population and density are higher, the extent of damage would be even greater. Thus the need to drastically improve the previous safety system was recognized.

The aims of new development were as follows:

1. Automatic shut down of low-pressure gas supply by means of district valves should be highly reliable.
2. Due to unavailability of technicians when an emergency occurs, the shut-down process should be completely automatic and telemonitored by headquarters.
3. A larger amount of earthquake motion data should be transmitted to headquarters for more accurate decision-making.
4. Earthquake motion and onset of liquefaction as sensed at 3,800 stations should be interpolated in surrounding areas by taking into account the effects of varying local geology. This enables the final decision to be made on a more regional basis.

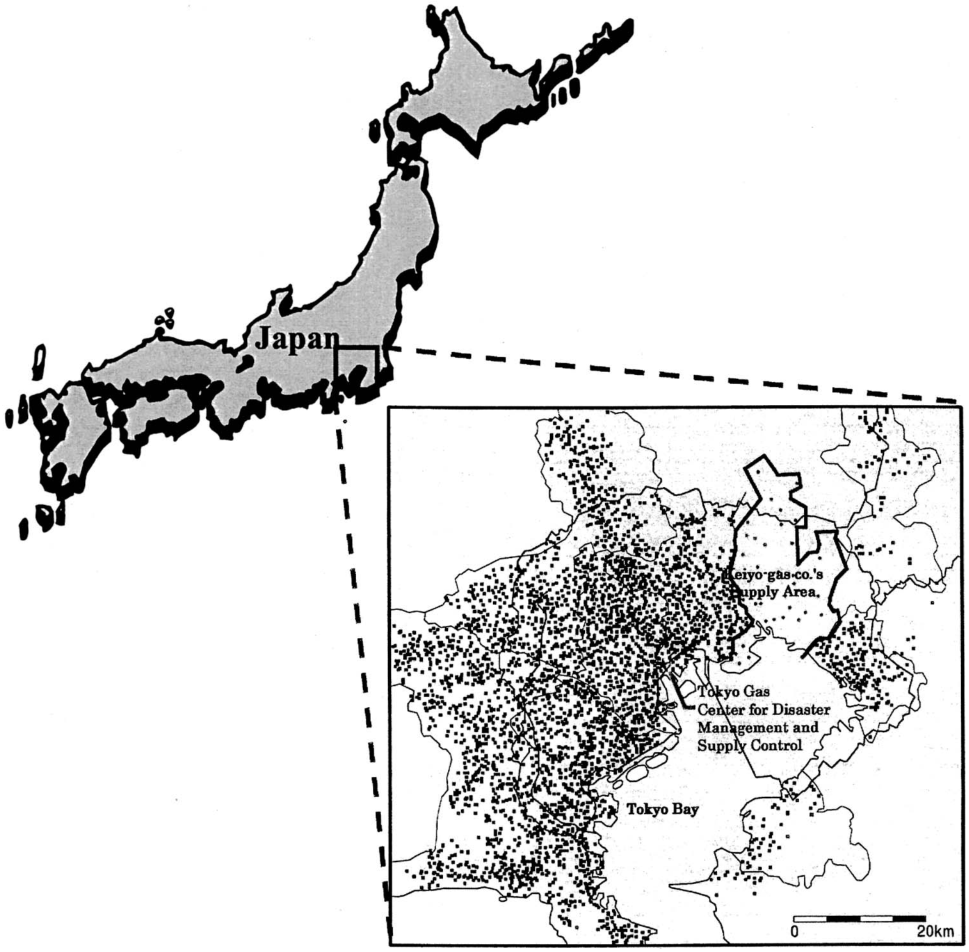

Fig. 2. Locations of 3,800 monitoring stations in *SUPREME* system

5. This interpolation procedure should be facilitated by the use of geographic information systems.
6. Data for minor earthquakes should be accumulated and analyzed in order to enhance expertise in the local nature of seismic response.

The new *SUPREME* system was developed within these parameters. It consists of new SI sensors and can perform real-time detection of onset of liquefaction based on the earthquake motion data. The SI devices together with the telemonitoring network and telecontrol system of gas valves were deployed at all the 3,800 district regulator stations (Fig. 2).

Structure of *SUPREME* System

The *SUPREME* system is characterized by the use of new SI sensors which can monitor and interpret the maximum peak ground acceleration (PGA), the time history of acceleration, and the SI on a real-time basis. They detect the symptoms of liquefaction in the subsoil from the recorded surface motion. These sensors are installed at all the 3,800 regulator stations which control the gas pressure in low-pressure pipes. Since the total service area is 3,100 km^2, there is, on average, one monitoring station per 0.9 km^2. There are also 20 liquefaction sensors that monitor the subsurface pore water pressure and detect liquefaction directly (Mori et al. 1997; Shimizu et al. 2002). Table 1 indicates the number of data sources in the system.

The communication between the sensors and headquarters where the shut-down decision is made by computer relies on two kinds of channels. One is a corporate wireless network and 332 stations are connected to this. The remaining 3,500 stations rely on the ordinary telephone network. Although the ordinary network is less reliable in seismic emergencies, cost-performance analysis made this feasible. A special provision against telecommunication congestion is made by getting a special privilege from the telephone company. Accordingly, it is projected that headquarters can receive 80% of needed information within 20 min of a quake. This rate of response was facilitated by developing a new data-communication unit (called DCX).

Table 1. Number of Data Collected by *SUPREME* (as of October 2005)

Type of data	Through wireless	Through telephone network
SI and acceleration	332 including 300 district regulator stations	3,500 new SI sensors
Onset of liquefaction	20 liquefaction sensors and 300 new SI sensors	3,500 new SI sensors
Gas pressure, flow, and shut-down	300	All the 3,800 district regulator stations

Note: To data, the *SUPREME* system uses SI from 3,500 stations out of monitoring at 3,800 regulators.

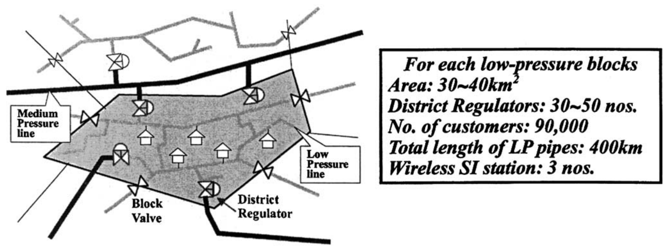

Fig. 3. Small block of low-pressurized gas supply

Specifications for New SI Sensor

The gas supply was shut off during the Kobe earthquake in areas where SI values greater than 59 cm/s were observed. Tokyo Gas policy is that the low-pressure gas supply in a regional block is immediately stopped when and where the SI value monitored through wireless communication exceeds 60 cm/s. If SI is between 30 and 60 cm/s, the decision is made carefully based on further information. To put this into practice, the low-pressure network in the service area of the company is divided into 101 blocks as illustrated in Fig. 3. Each block has an area of 30–40 km^2, including 30–50 district regulators. In an emergency, the gas supply is stopped completely by closing all the regulator valves in the block. Moreover, each small district is independently shut off automatically at 30–40 cm/s. To ensure reliability, each block area has at least three wireless SI monitoring stations. The monitored SI value is transmitted to headquarters so that headquarters may make shut-down decisions. Very high reliability is required for SI monitoring because unnecessary shut down causes inconvenience to customers, and resuming gas supply after a shut down requires inspection of all customers in the area as a safety measure.

The new SI sensor for the *SUPREME* system (Fig. 4) provides the following improvements over its former version:

1. It is cased in a waterproof container which can withstand explosion nearby and is effectively insulated from electromagnetic noise. The total weight, inclusive of the container, is only 1.3 kgf.
2. The thermal effects on sensitivity of accelerometers are corrected for by monitoring temperature.
3. Acceleration time histories in three orthogonal directions are monitored. The sampling interval is 10 ms, the sensitivity is $1/8\ cm/s^2$, and duration of recording is 120 s.
4. Sensing parts and calculators are combined into one piece, enabling the SI value to be obtained within the device.
5. Records of ten past earthquakes are stored in the memory. The ten records stored are those for the earthquakes with 10 biggest SI values.
6. An algorithm to infer the onset of subsoil liquefaction is incorporated into the sensor unit. This approach is cheaper than that used in the previous version of liquefaction sensor, which required a bore hole to be drilled for installation.

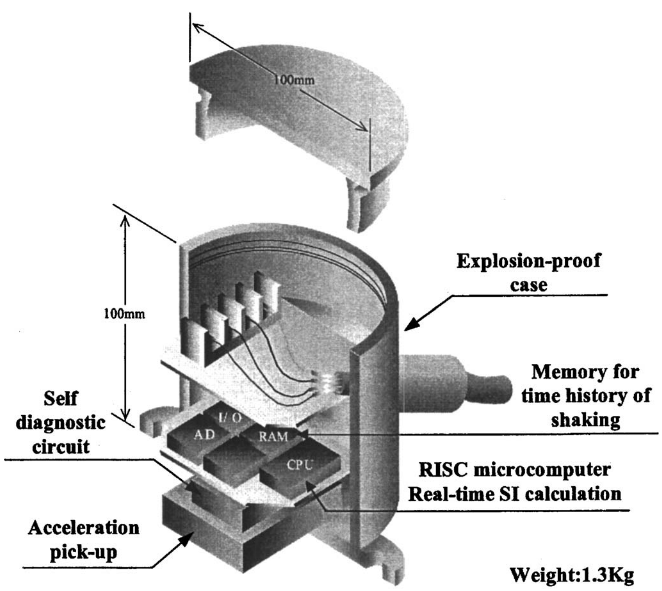

Fig. 4. Sketch of new SI sensor

Automated Shut-Down of Regulator Valves

The former *SIGNAL* version only automatically closed regulator valves based on SI at regulator sites. Since there are 30–50 regulators in each low-pressure block, it was not possible to completely stop the gas supply unless all the regulators were closed. The problem was that some regulators may not be shaken so substantially, with the result that their valves remain open. Another problem was the reliability of automatic closing of valves, which made it necessary to send technicians to the regulator sites in order to make sure that the valves had closed. This procedure requiring human intervention becomes significantly more difficult after a big earthquake when it is most important that the system functions properly.

The *SUPREME* system has achieved the goal of perfect isolation of low-pressure blocks. The newly developed regulator telecontrol system sends signals to close the valves through the telephone network. Safety measures have been installed to handle wrong signals, malfunctioning, and the effects of hackers. At the same time, the conventional valve-closing mechanism based on SI values on site is still working. Thus, regulators are closed through two means; an individual automatic system based on SI, and a remote shut-off system through *SUPREME*. This approach avoids the need to send technicians.

Simulations were made to investigate the time elapsed before completing the shut off and isolating the region. Magnitude 7.2 earthquake below Tokyo (latitude: 35°38′11″, longitude: 139°50′10″, depth: 20.0 km) was assumed to calculate ground motion. SI value at base rock was estimated using an attenuation formula:

$$\log(\mathrm{SI}) = -0.785 + 0.491M - 0.00146r - \log(r) + 0.00359h + ci$$

where M=magnitude; r=hypocentral distance; h=depth; and ci=site amplification factor (ci=−0.251 at Vs=600 m/s), where Vs=shear wave velocity. SI value at ground surface is estimated

Table 2. Empirical Assessment of Number of Technicians Available for Emergency Inspection

Elapsed time after earthquake (h)	2	4	6	12	24	36	48
In damaged area (%)	8	20	26	31	31	62	100
In undamaged area (%)	12	43	57	70	70	85	100

Note: Based on the 1995 Kobe earthquake.

by multiplying the site amplification factor (described in the following) with the SI value at base rock. The number of district regulators expected to be shut down is estimated from the simulated SI value.

According to this calculation, when there are 1,200 district regulators in a region, 850 of them are automatically closed immediately. To close the remaining 350 valves, without *SUPREME*, a huge amount of human labor would be needed. However, the empirical assessment in Table 2 shows that a long time is necessary for technicians to start operation. In contrast, less than 1 h is necessary for *SUPREME*.

The proportion of telephone lines damaged was assumed to be 5%, with reference to the damage experienced during the Kobe earthquake. Technicians only need to be dispatched to regulators where telecommunication lines are damaged and manual closing is required.

Interpolation of Monitored SI Values

In the *SUPREME* system, there is only one monitoring station for every 0.9 km^2 of the service area, and it is difficult to infer the extent of damage in an area using just the data from a single station. To overcome this problem by interpolating data among stations, a geographic information system (GIS) has been introduced.

The present GIS has subsoil data from 60,000 boreholes. Partially gathered by Tokyo Gas and partially supplied by municipalities in the service area, the digitized borehole information consists of the location, depth, types of soil, standard penetration test (SPT) blow counts, surface elevation, and elevation of the ground water table. This has enabled microzonation of the area based on individual borehole data (Fig. 5). Note that seismic amplification is strongly affected by the thickness and properties of surface soils. Moreover, the type of surface quarternary geology—alluvial plane, abandoned river channels, natural levee, or other—affects the liquefaction potential (e.g., Wakamatsu 1991).

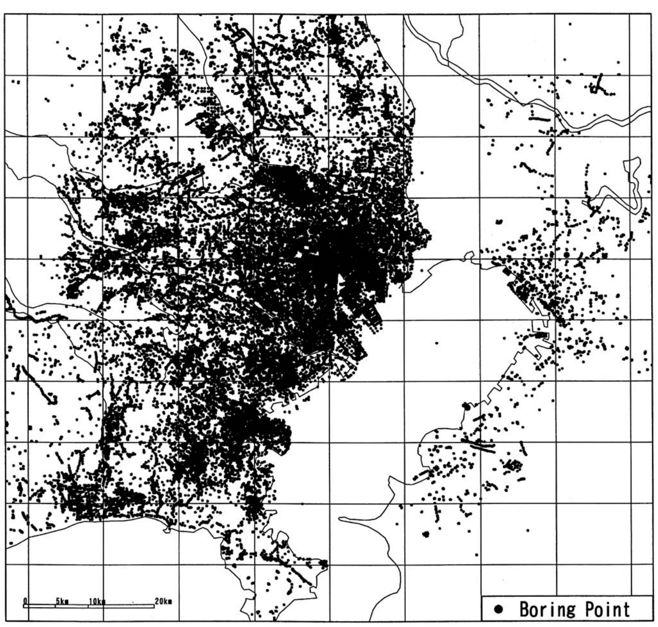

Fig. 5. Sites of boreholes employed in *SUPREME*

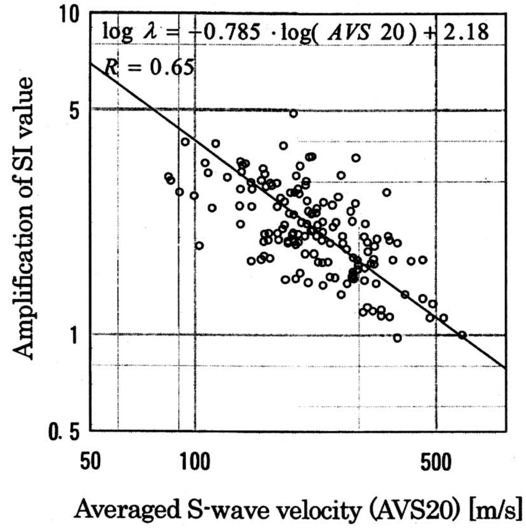

Fig. 6. Amplification of SI value between base and ground surface (empirical data in Yokohama City and newly proposed formula)

To assess the possibility of liquefaction at places where seismic motion is monitored, interpolation of SI values is made in the following manner. SI at 3,800 sites of monitoring has to be converted to the value at 60,000 borehole sites where no monitoring is run. To achieve this goal, first the average S-wave velocity (denoted by $V_{s,20}$) in the top 20 m soil of a borehole site is assessed by

$$\frac{20}{\bar{V}_{s,20}} = \sum_i \frac{H_i}{V_{s,i}} \tag{2}$$

in which the top 20 m of soil consists of sublayers each of which has a thickness of H_i and S-wave velocity of $V_{s,i}$. Since V_s values are seldom measured in practice, empirical formulas are used to assess them from SPT-N values (Japan Road Association 1996); for sandy soils:

$$V_s = 80N^{1/3} \quad \text{(m/s)} \tag{3a}$$

for clayey soils:

$$V_s = 100N^{1/3} \quad \text{(m/s)} \tag{3b}$$

Then, the averaged $V_{s,20}$ is substituted in the empirical relationship in Fig. 6 which was obtained from earthquake monitoring at 150 stations in Yokohama City (Tamura et al. 2000). Note that Yokohama is in the Tokyo Gas supply area and detailed earthquake monitoring and ground investigations have been made

$$\lambda = \frac{\text{SI(surface)}}{\text{SI(base)}} \approx -0.785 \log_{10}(\bar{V}_{s,20}) + 2.18 \tag{4}$$

where the base stands for an engineering base with V_s being 600 m/s or more. By using this amplification, SI monitored at the ground surface is converted to that at the base, which is again converted to SI at the surface of any nearby borehole site;

$$\begin{aligned}\text{SI(borehole site)} &= \lambda\text{(borehole site)} \times \text{SI(Base)}\\ &= \lambda\text{(borehole site)} \times \left(\frac{\text{monitored SI}}{\lambda \text{ at monitoring station}}\right)\end{aligned} \tag{5}$$

Note that Eq. (5) assumes common values of SI in the engineer-

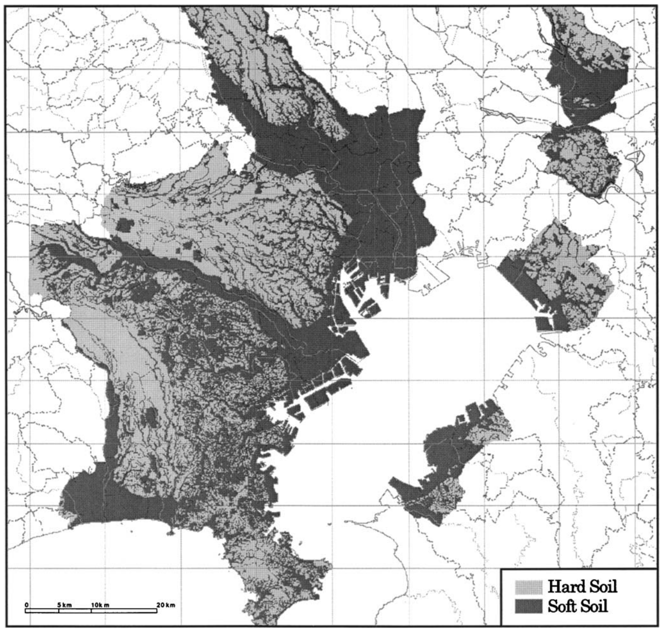

Fig. 7. Classified simplified surface geology in Tokyo and surrounding area

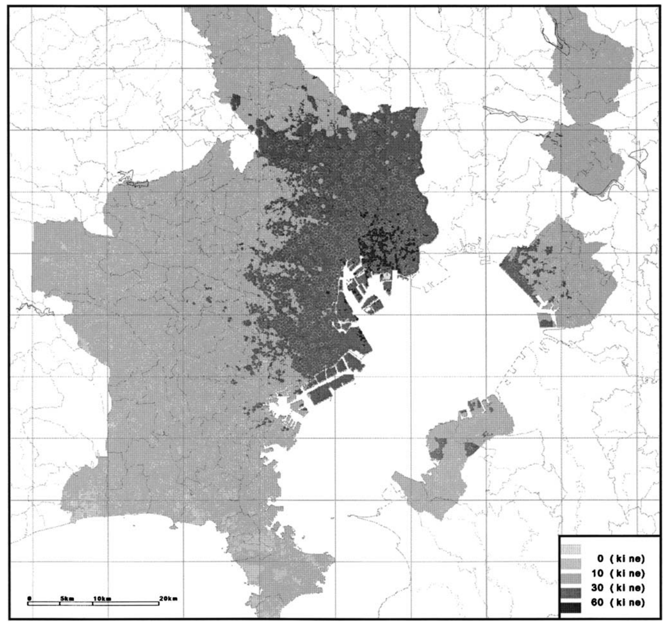

Fig. 8. Simulation of SI values in service area

ing base at both monitoring and borehole sites due to their short distance.

The surface SI at the place of interest is interpolated from SI at borehole sites. To carry this out, the surface geology in the concerned area is classified into two groups and interpolation is made separately. This is reasonable because the type of surface geology significantly affects the seismic amplification. The first geological grouping is the sites with harder soil. In Tokyo and surrounding areas, these are hill and terrace sites. The second group is the sites with softer material. These are alluvial plains, natural levees, back marshes, abandoned river channels, land reclamations, small valleys between hills, and similar sites. Fig. 7 illustrates the two groups of hard and soft geologies in the service area of the company. To complete the interpolation, five nearest borehole stations within 5 km from the place of interest are picked up from the same geological group. When the distance from those reference stations to the place of interest is denoted by r_i, the interpolated SI is given by

$$\mathrm{SI} = \frac{\displaystyle\sum_{i=1}^{5} \frac{\mathrm{SI}(\text{at borehole site } i)}{r_i^2}}{\displaystyle\sum_{i=1}^{5} \frac{1}{r_i^2}} \tag{6}$$

where $1/r_i^2$ is used for the purpose of giving more weight to the data at closer borehole sites. Appendix II supports this idea.

Combining Eqs. (5) and (6) gives the interpolated SI value at any site of concern. Finally, Fig. 8 was obtained from a simulation in which an earthquake of magnitude 7.2 occurs under the center of Tokyo. Past earthquake experiences gave a relationship between SI and the number of pipeline failures. Thus, the extent of damage can be assessed from the SI values, which helps shutdown decision making.

Assessment of Onset of Liquefaction

In addition to intensity of shaking described in the previous section, liquefaction is a very important cause of damage to buried pipelines. Most probably, the causative mechanism of pipeline damage is the ground distortion related to liquefaction. It is, however, difficult to assess ground distortion along low-pressure pipes of more than 40,000 km; it is intended to work on the extent of liquefaction for practice. Therefore, it is essential that *SUPREME* assesses the onset and extent of liquefaction by using telemonitored information. The first achievement in this line was made by using a liquefaction sensor (Shimizu et al. 2002). The liquefaction sensor is a device which can quickly detect the occurrence and extent of liquefaction during earthquakes as shown in Fig. 9. This sensor detects soil liquefaction through the rise of water level inside a hollow embedded pipe and the increase of air pressure inside the pipe. This hollow pipe has a filter at the middle of a liquefiable sandy layer, and a water level transducer and pressure gauge situated above the ground surface.

Although the use of liquefaction sensors is direct and clear, the problem was the need for drilling boreholes and the increased cost of installation, which made it impossible to deploy them at hundreds of sites in the service area. Hence, a second approach has been taken in which the interpretation is made of monitored earthquake motion. It should be borne in mind that the extent of liquefaction damage depends not only on the onset of liquefaction but on the thickness of liquefied soil.

Towhata et al. (1996) analyzed earthquake motion records and carried out shaking table model tests in order to assess the thickness of liquefied subsoil. By using the maximum horizontal acceleration, $A_{\max}$, and SI as observed at the ground surface, the proposed method consists of two formulas; amplitude of horizontal displacement

$$D_{\max} = \frac{2\mathrm{SI}^2}{A_{\max}} \tag{7}$$

The use of Eq. (7) directly calculates $D_{\max}$. The time saving effect is significant as compared with double integration of the entire

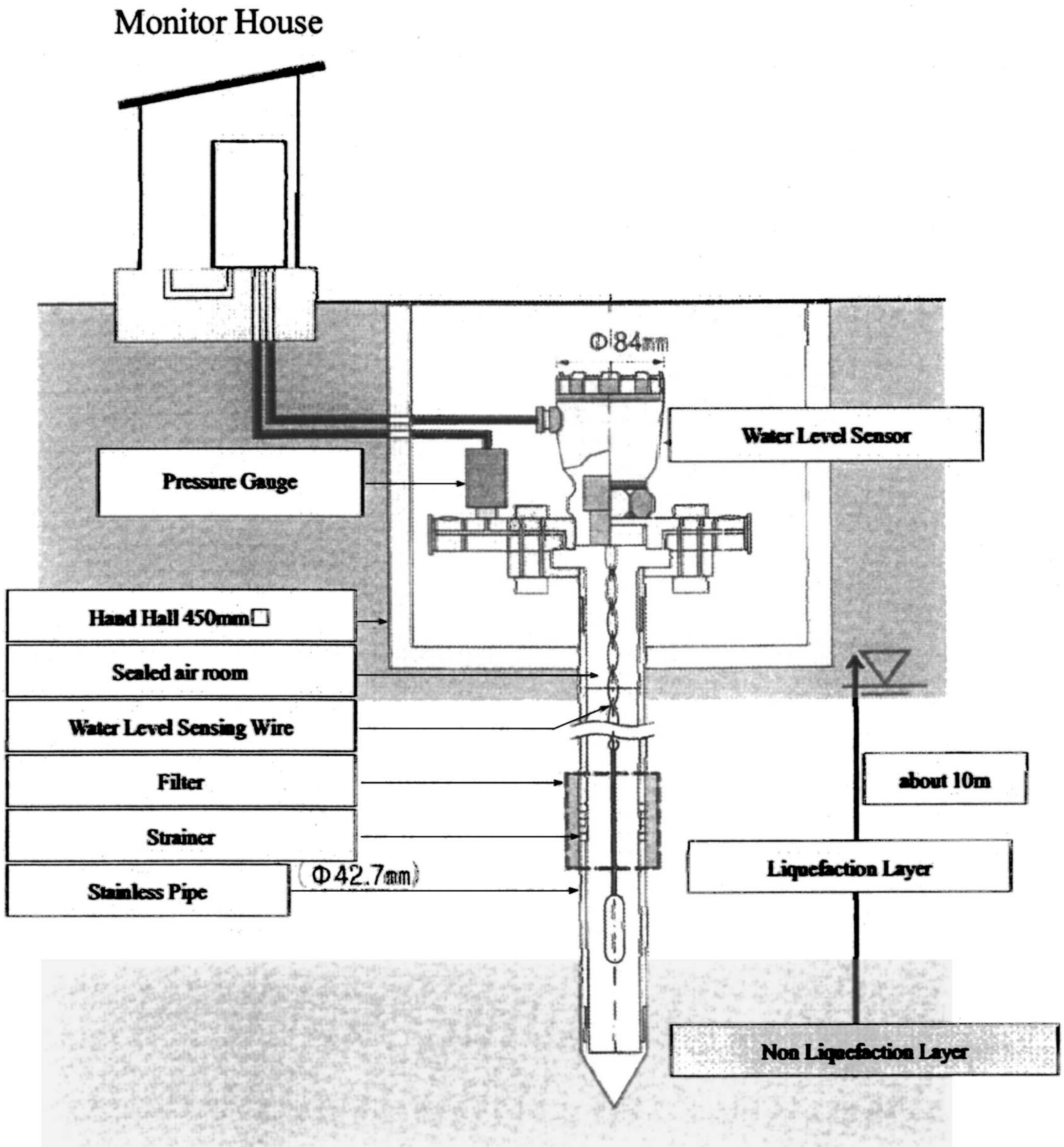

Fig. 9. Sketch of liquefaction sensor

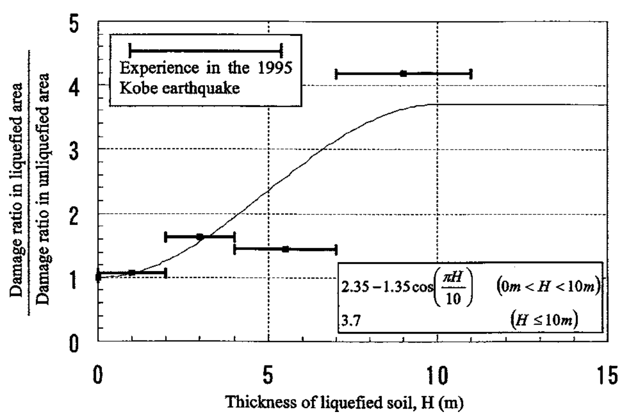

Fig. 10. Relationship between damage ratio change and the thickness of liquefied soil, H

acceleration time history, moreover, such problems as base-line correction and filtering are avoided. Then, the thickness of liquefied soil, H, is simply assessed by

$$H = \frac{\pi D_{max}}{2\gamma_{liq}} \tag{8}$$

where γ_{liq}=amplitude of shear strain at the onset of liquefaction and is set equal to 0.01875; this is equivalent to double amplitude of 2.5% in undrained cyclic triaxial tests. Hosokawa et al. (2001) analyzed pipeline damages during past earthquakes that damage rate increases with H: see Fig. 10. Eq. (8) is valid for a simple situation where there is no dry unliquefied crust at the surface. It was also stated that no liquefaction is likely when SI is less than 15 cm/s.

When this method was compared with case histories, it was noticed that the assessed thickness of liquefaction tended to be an overestimation. This is illustrated in Eq. (8), where even the minor value of displacement, D_{max}, suggests some thickness of liquefaction. It is likely in reality that small deformation of sand

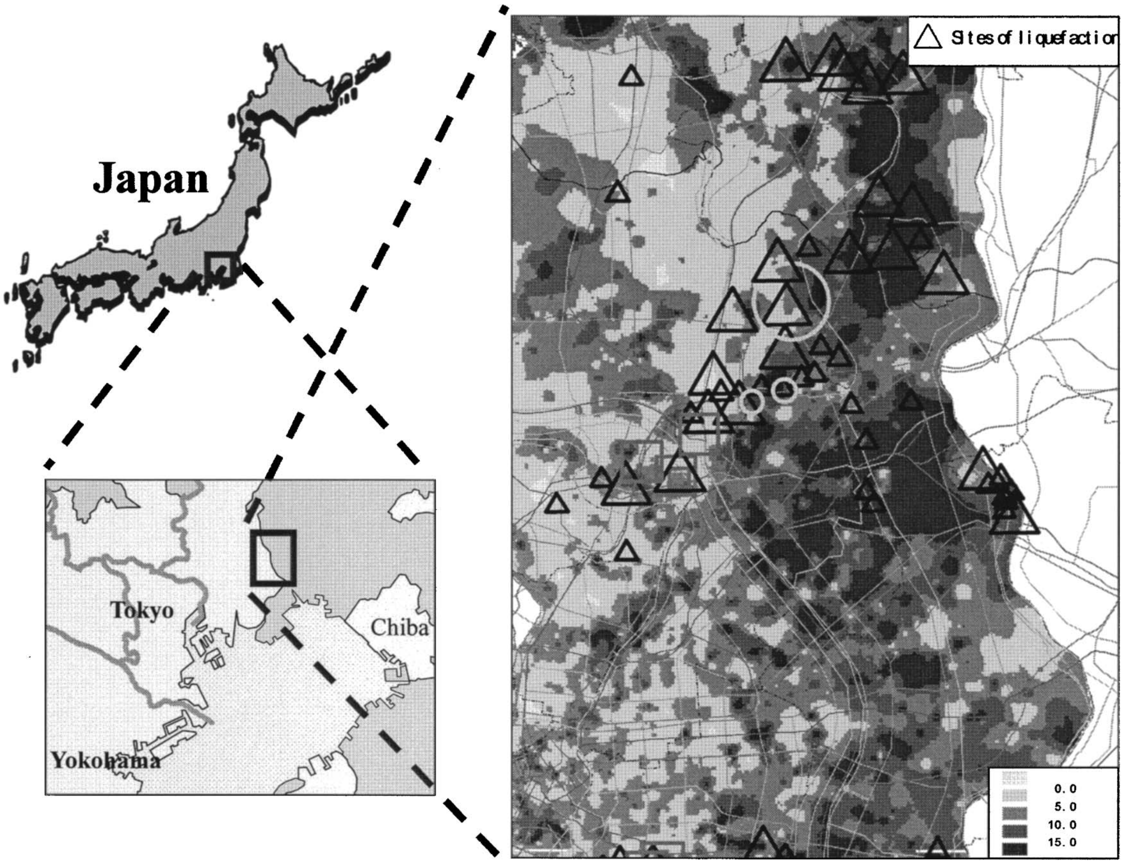

Fig. 11. P_L distribution (surface acceleration of 0.4 G was assumed)

does not cause liquefaction. Hence, D_{max} and γ_{liq} in Eq. (8) should have components which are not related to liquefaction subtracted. In the present study, therefore, γ_{liq} is replaced by $\gamma_{liq}-0.01$ and D_{max} by $D_{max}-5$ (cm). Therefore,

$$H=\frac{\pi\left(\dfrac{2\mathrm{SI}^2}{A_{max}}-5\right)}{2(\gamma_{liq}-0.01)}\div 100 \quad \text{(m)} \tag{9}$$

Note that SI and A_{max} use centimeters and seconds as units. The assessed range of liquefaction starts from the ground water table to the depth of H below it.

Another important issue in application of Eq. (9) is that the assessed range of liquefaction should be limited by the thickness of loose sand deposits. In other words, the assessed liquefied layer should not include such unliquefiable soils as dense sand, clay, and Pleistocene materials underlying loose sand. With this viewpoint, 60,000 boring profiles in the present GIS database were analyzed to determine the maximum possible thickness of liquefaction. This was attained by re-interpreting past liquefaction test results on undisturbed soil samples in relation to SPT-N, etc. and developing a new regression formula specific to the Tokyo area (Kamei et al. 2002). Consequently, the factor of safety, F_L, was calculated by using 0.4 G surface acceleration, and its weighted average in the vertical direction, P_L, was obtained and illustrated in Fig. 11 (Tatsuoka et al. 1980)

$$P_L=\int_0^{20}\mathrm{Max}(0,1-F_L)(1-0.05z)dz \tag{10}$$

where $\mathrm{Max}(0,1-F_L)$ means the greater value of 0 and $1-F_L$; while z=depth (m); and P_L=index which accounts somehow for

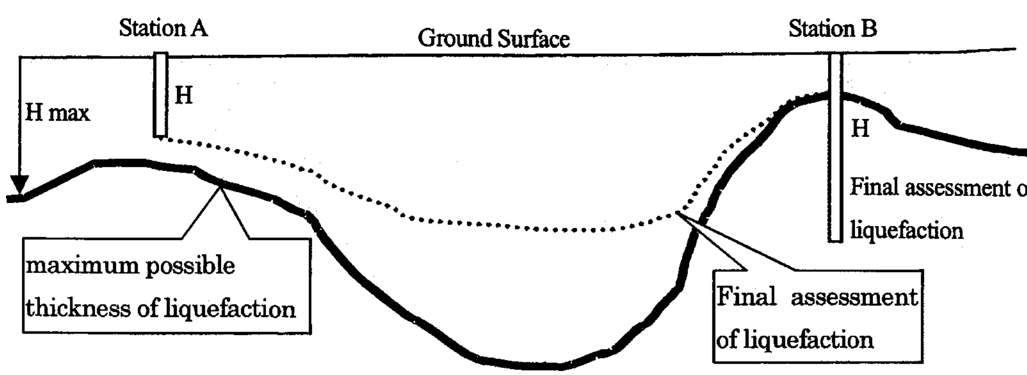

Fig. 12. Interpolation of assessed thickness of liquefaction

Table 3. Assessment of Damage Rate of Pipelines Undergoing Very Strong Earthquake

Coefficient	Value	Item
C1	1.0	For screw-joint steel pipe
(type of pipeline joints)	0.83	For bell-joint cast iron pipe
	0.27	For frange-joint ductile cast iron pipe
	0.02	For mechanical-joint ductile cast iron pipe
	0.07	For mechanical-joint steel pipe
C2	1.65	For cuts and fills in hill/terrace area
(surface geology)	2.24	In narrow valleys (width < several hundred meters) in hilly area
	1.00	For alluvial plane with SPT-N < 10
	0.87	For alluvial deposit with SPT- > 10
C3	$2.35-1.35\cos(\pi H/10)$	When the assessed thickness of liquefaction (H) < 10 m
(extent of liquefaction)		
	3.7	When $H>10$ m
R_0	2.36	The peak damage rate for screw-joint steel pipe
(peak damage rate)		buried at alluvial plane with SPT-N < 10

Note: $\phi(\mathrm{SI})=[\log_e(\mathrm{SI})-4.305]/0.509$.

the overall effects of liquefaction. There is a correlation between P_L and the distribution of sites of liquefaction during the 1923 Kanto earthquake (Fig. 11). Note that sites of eyewitnessed liquefaction are well estimated with a reasonable safety margin. It should be borne in mind that more liquefaction might be missed in Fig. 11 due to lack of eyewitness evidence in this then less populated area. Fig. 12 illustrates the method of interpolation for thickness of liquefaction when the assessed thickness (H) exceeds the maximum possible thickness ($H_{\max}$). It is seen there that the ratio of $H/H_{\max}$ is interpolated from Station A to B in order to obtain the final assessment of the thickness of liquefaction.

Decision Making

The final decision has to be made as to whether or not the low-pressure gas supply in the concerned block is stopped by telecontrol closing of regulator valves. For this aim, a special logic was constructed.

The rate of damage to embedded low-pressure pipelines is assessed by the following formula with a simple but practical structure;

$$R=R_0C_1C_2C_3\phi(\mathrm{SI}) \tag{11}$$

in which R=number of damage points per 1 km length of pipeline; R_0=control damage rate being equal to 2.36/km; whereas C1, C2, and C3 parameters account for the effects of types of pipeline joints, surface geology, and thickness of liquefied soil. Moreover, ϕ=function varying with assessed SI at the surface. The Kobe earthquake gave us information for the first time about damage to pipelines caused by extremely strong ground motions of over 100 cm/s as well as measured SI values. With as strong an earthquake as the one in Kobe in mind, the pipeline damage records in the Kobe area were analyzed to obtain parameters in Eq. (11). ϕ(SI) for screw-joint steel pipe in alluvial plain without liquefaction was determined first based on the 1995 Kobe, the 1993 Kushiro, and the 1978 Miyagi-Ken-Oki earthquakes, among others. The parameters for the type of pipeline joints, surface geology, and extent of liquefaction were then determined by comparing damage ratios. (See Table 3 for details.) Fig. 13 compares Eq. (11) with experienced damage rates for cut-and-fill areas and alluvial plains. Damage starts at 30–40 cm/s, which validates prior discussion. The Kobe earthquake is particularly important to Tokyo because Kobe has almost the same lifeline systems as Tokyo.

Performance of Supreme System during Earthquakes in Taiwan

The *SUPREME* and new SI sensors have been installed in Taiwan. The Great Taipei Gas Company had 31 new SI sensors with telemeter using leased telephone line at the time of 1999 Chi-Chi earthquake and the time histories of acceleration and SI values were recorded. The *SUPREME* system judged that there was no need to shut off the gas supply, and in reality there was no damage except in a few minor cases. Fig. 14 shows the distribution of the observed ground motion.

A comparison was made of acceleration time histories obtained by SI sensors at two sites; Shazoo lying on soft subsoil and Yenson on base rock. Boring data from these two sites is presented in Fig. 15. Although the former site has SPT-N less than 20 down to the depth of 40 m, the latter has a much stiffer subsoil.

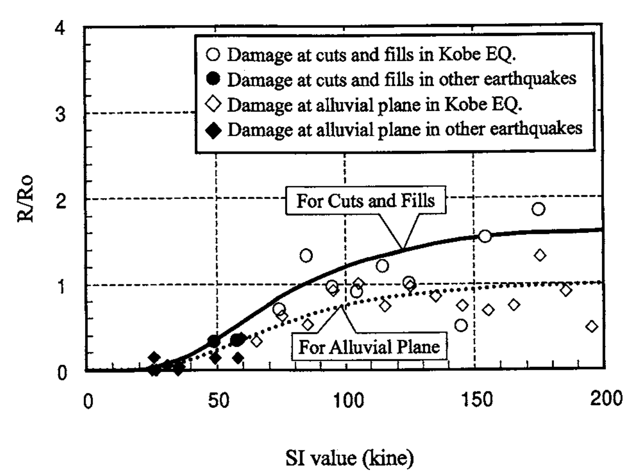

Fig. 13. Comparison of damage rate for screw-joint pipes between assessment and experiences [after Hosokawa et al. (2001)]

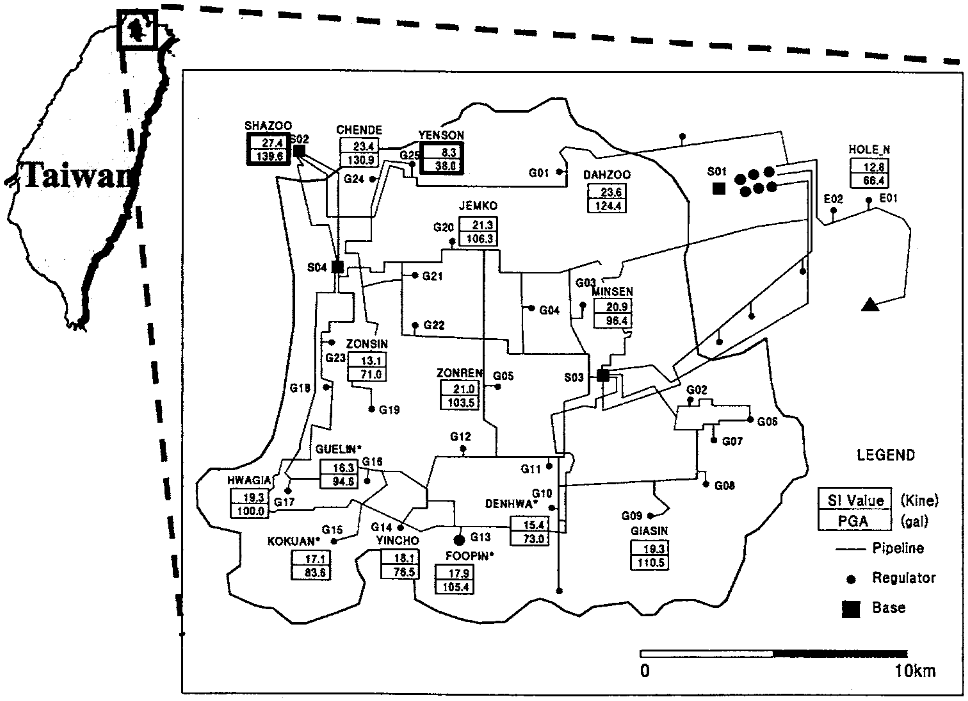

Fig. 14. Distribution of SI and PGA observed in Taipei City during the 1999 Chi-Chi earthquake

Both sites are located in the north part of Taipei City and their distances from the seismic fault are similar. Therefore, any significant difference in the recorded motion can be attributed to local geological conditions. It is apparent in Fig. 16 that the intensity of acceleration on the soft soil deposit (Shazoo) was much greater than that on firm ground (Yenson). Acceleration response spectra of these records are also illustrated in Fig. 16. The stronger component in the range of shorter natural period is noteworthy in the Shazoo record.

In March, 2002, another big quake called 331 Earthquake hit Taipei City. The earthquake motion in Taipei City was monitored again by new SI sensors, and it was stronger than that of Chi-Chi earthquake. SI values were 23.0 and 10.8 cm/s at the Shazoo and Yenson sites. At Hshinya district regulator station, the monitored SI value was 36.5, which exceeded the threshold SI for automatic shut-off. Accordingly, the valve was closed automatically as was designed by *SUPREME*. There were actually some minor leakages in low-pressure network near Hshinya, so *SUPREME* was proved to be useful.

Future Development

SUPREME will continue to be developed in order to achieve higher reliability. One of the efforts is oriented toward detecting onset of liquefaction by using surface motion records. Several

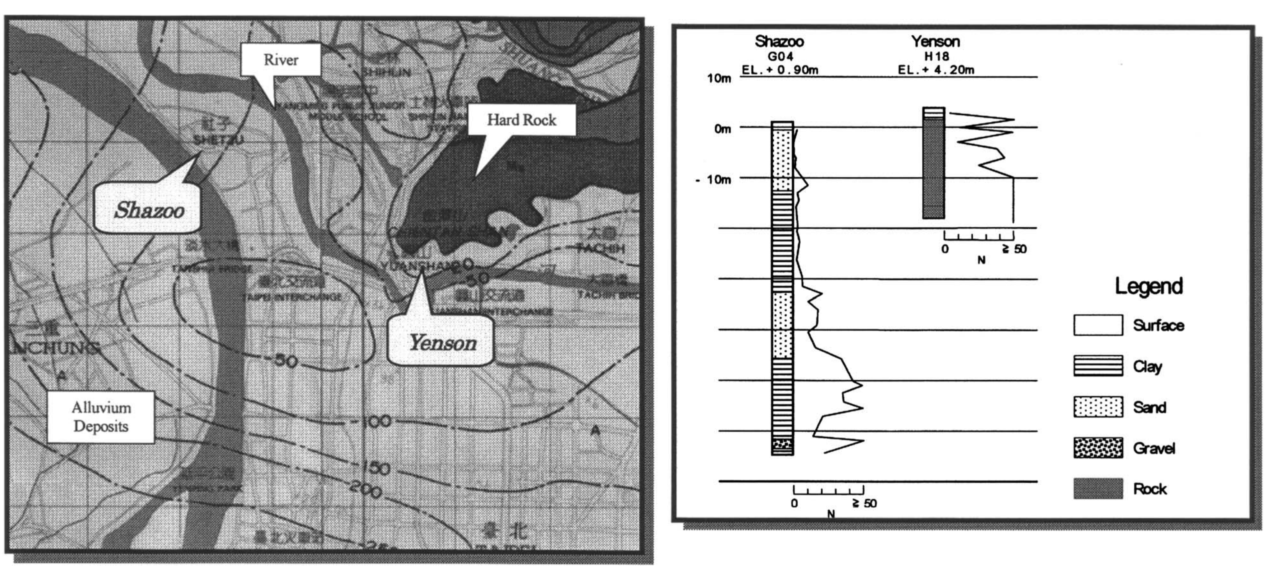

Fig. 15. Boring data at Shazoo and Yenson

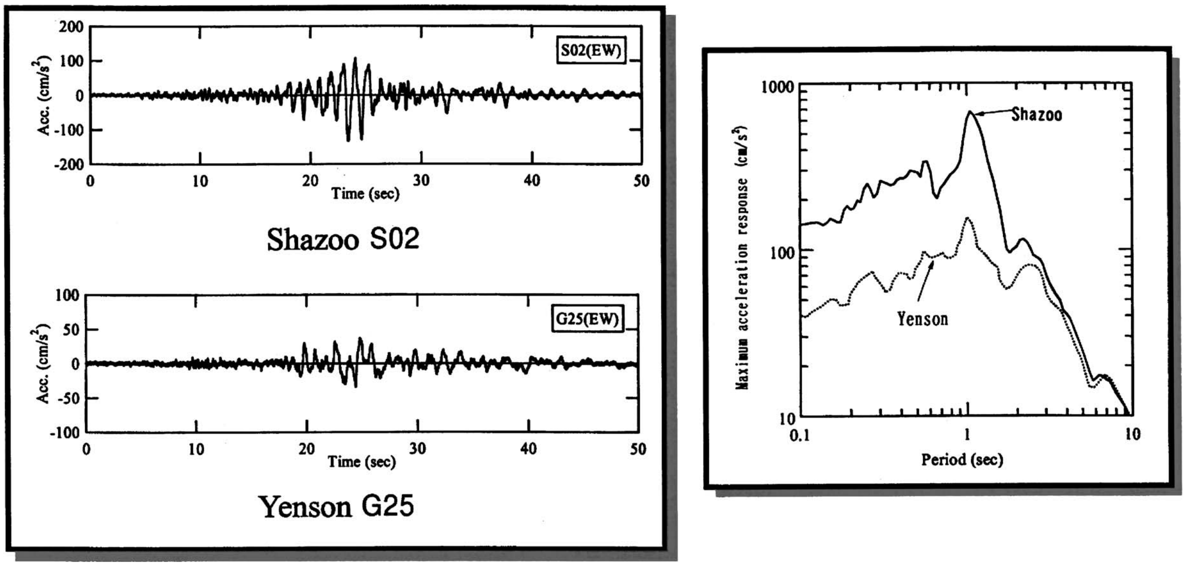

Fig. 16. Acceleration response spectra at Shazoo and Yenson

records of strong motion data observed on liquefied subsoil, from Niigata, Kobe, etc. have specific features in acceleration time histories. Consequently, several methods for detecting liquefaction from the appearance of time histories have been proposed (Miyajima et al. 2000; Takada and Ozaki 2000; Kostadinov et al. 2001). However, since they need the whole time history of acceleration, it is difficult to use them in an emergency situation on a real-time basis.

It is reasonable that the intensity of acceleration prior to the occurrence of liquefaction has to be strong enough to cause liquefaction. Therefore, the maximum acceleration and SI value should be greater than certain levels. Second, the subsurface liquefaction reduces the magnitude of surface horizontal acceleration, and the period of acceleration record is elongated. Consequently, the amplitude of displacement becomes large. Analyzing 45 earthquake motion records, among which 19 were obtained near a site of liquefaction such as Kawagishicho in Niigata and Port Island in Kobe, an attempt is being made to propose criteria for detecting onset of liquefaction.

Four parameters have been studied, the PGA, the SI value, the maximum value of zero crossing period (T_z) and the assessed amplitude of displacement (D_{max}). The third parameter, T_z, is intended to detect the change of shaking frequency, which is 2× (the longest time interval between one zero crossing time and the next). The fourth parameter, D_{max}, is estimated by Eq. (7).

The studies by Suzuki et al. (1998) have so far shown that the simultaneous occurrence of PGA > 100 gal, SI > 20 kine, $D_{max} > 10$ cm, and $T_z > 2.0$ s is the criterion that characterizes the onset of subsurface liquefaction. Fig. 17 shows the relationship between T_z, D_{max}, and the onset of liquefaction. In Fig. 17, "Liquefaction" stands for cases where the real liquefaction was successfully detected by the combination of the four parameters. On the other hand, "Missing" indicates a wrong judgment where liquefaction was not suggested although it did occur, or liquefaction did not occur contrary to judgment. "None" means that no liquefaction was suggested and it did not occur in reality either. Wrong judgment was made in five cases; three missed actual liquefaction in reality and two predicted liquefaction which did not occur. The latter two concern the Mexico City record (SC&T) during the Michoacan Earthquake in 1985 and ShiGang record during the 1999 ChiChi earthquake. It seems that the large amplitude of surface wave or fault movement therein led to wrong judgments. These studies imply that the proposed criterion can be used for practice with reasonable reliability.

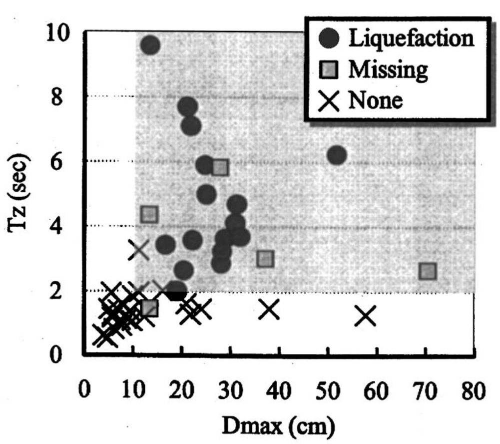

Fig. 17. Relationship between T_Z, D_{max} and the onset of liquefaction

Concluding Remarks

A real-time safety control system, *SUPREME*, with 3,800 new SI sensors was developed in order to counter earthquake-induced hazards in a city gas supply network. The system is characterized by the combination of geotechnical earthquake engineering and information technology. The major achievements are as follows.

1. Quick shut down of gas supply is achieved by automatic control of new SI sensors and telecontrol of gas supply valves.
2. This goal is attained by the development of a new SI sensor which interprets recorded motions and detects the onset of liquefaction in the subsoil.
3. The real-time geographically dense earthquake motion monitoring and ample soil data provided by a GIS play the chief role in determining the spatial distribution of SI values and

extent of liquefaction over a vast service area, enabling identification of the areas where pipeline breakage is likely due to shaking and liquefaction.

4. The extent of damage in gas pipelines is assessed immediately after an earthquake by using a substantial amount of borehole data as well as past experience of pipeline breakages.
5. Good performance of the system was demonstrated during recent Taiwan earthquakes.

Acknowledgments

A substantial amount of borehole data was supplied to the writers by many municipalities, including the Tokyo metropolitan government, Yokohama City, Chiba City, Kawasaki City, Kanagawa Prefecture, and Saitama Prefecture. Cooperation with the Great Taipei Gas Company has made it possible to demonstrate the satisfactory performance of the *SUPREME* system. The development of the system was significantly promoted by discussion conducted at the Association for Development of Earthquake Prediction with Dr. T. Katayama, Mr. J. Ikeda, and Ms. Y. Ogawa. The writers deeply appreciate all the assistance and cooperation kindly provided by governments, institutes, and individuals.

Appendix I. Real-Time Algorithm in SI Sensor

Since the task of SI sensors is conducted in a real-time basis, special cares were taken of time and memory saving. First, the calculation of SI based on Eq. (1) was carried out not over the entire duration of shaking but on moving time windows of 20 s. Table 4 shows the magnitude of possible errors in SI calculated on 60 seismic records. It is therein seen that the window length of 12 s achieves in error of less than 1%. Thus, 20 s for *SUPREME* is sufficiently long.

The *SUPREME* system intends to detect the direction of horizontal shaking that gives the maximum SI value in the horizontal plane. To achieve this goal, SI should be calculated in as many as possible directions of motions in the horizontal plane. This is, however, a time consuming issue. To overcome this problem, Table 5 was obtained which shows that calculation and detecting the maximum SI value out of eight directions is sufficiently accurate as compared with similar calculations on 180 directions.

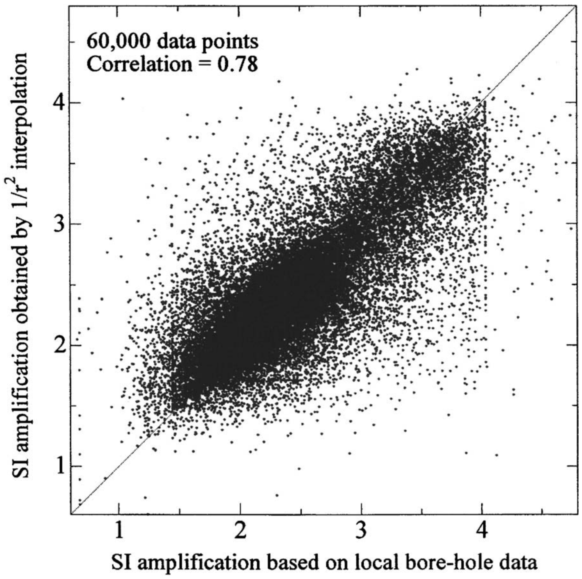

Fig. 18. Relationship between SI amplifications obtained by interpolation and based on local borehole data

The calculation of SI based on Eq. (1) requires the velocity response to be obtained at a variety of natural period, T. This calculation is again time consuming and attempts were made to some this time. Table 6 shows that the use of only two values of T leads to 12.9% error. When seven values were chosen unevenly at 0.1, 0.4, 0.7, 1.0, 1.5, 2.0, and 2.5 s, the associating error was smaller than that with an even interval of T. Thus, *SUPREME* employs this uneven and efficient choice of T.

In conclusion, the present efforts shortened the necessary computation time and reduced the required memory size from 180 to 0.7 kbytes. Hence, real-time computations become possible.

Appendix II. Robustness of SI Interpolation

The validity of Eq. (6) was examined by using 60,000 bore-hole data. Fig. 18 compares the SI amplification (Fig. 6). Most data out of 60,000 show practically good agreement.

Table 4. Time Window Lengths for SI Calculation and Associating Errors with 60 Earthquake Records

Time window length (s)	4.0	6.0	7.0	8.0	9.0	10.0	12.0
SI calculation error (%)	2.0	1.5	1.3	1.2	1.1	1.0	0.9

Table 5. Number of Horizontal Directions for SI Calculation and Associating Errors with 60 Earthquake Records

SI calculation vector	2	4	5	6	8	9	12	180
SI calculation error (%)	39.9	2.5	1.9	1.6	1.0	1.0	0.9	0.0

Table 6. Number of Natural Periods in SI Calculation and Errors Associating with 60 Earthquake Records

SI calculation vector	2	4	5	7	7[a]	13	25	49	121
SI calculation error (%)	12.9	7.9	4.9	2.4	2.2	2.2	1.1	1.1	1.1

[a]Natural vibration based on uneven interval.

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