Development of SIGNAL:
An Early Warning System of City Gas Network

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Abstract

An earthquake monitoring and early warning system for a large-scale city gas network has been developed in the Tokyo Metropolitan area. The monitoring system consists of 356 earthquake sensors. Once an earthquake occurs, values monitored by these sensors will be sent to the supply control center by radio. Then estimation of damage to customers' buildings and pipelines, estimation of the magnitude and hypocenter, evaluation of the response spectrum, and decision analysis whether to shut-off or maintain the supply will be conducted. The system will play an important role in mitigating gas-related secondary disasters due to earthquakes.

Introduction

The 1995 Great Hanshin Earthquake caused serious damage to the natural gas system in the Kobe area. Numerous breaks in distribution lines were reported. Full service restoration took about 2.5 months. To cope with secondary disasters after an earthquake, city gas companies in Japan have promoted several countermeasures: increasing seismic resistance of facilities and pipelines, segmentation of networks into blocks, earthquake monitoring by seismometers, etc. This paper describes a real-time earthquake monitoring and early warning system of Tokyo Gas, called SIGNAL (Seismic Information Gathering and Network Alert).

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Segmentation of gas networks is carried out in two stages: one for medium-pressure lines and another for low-pressure 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. Emergency shutoff of gas systems has been conducted based on damage reports. However, since the service areas of city gas systems have grown, it may take too much time to detect actual damage. Hence, real-time damage assessment based on earthquake monitoring was considered. For low-pressure lines, emergency shutoff is carried out automatically based on measured spectrum intensity (SI) values at district regulators. 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. Thus, on-line damage assessment based on extensive monitoring was considered (Yamazaki et al., 1994a).

Earthquake Monitoring

The service area of Tokyo Gas with 8.0 million customers is divided into nine K-blocks (Figure 1). Each K-block has regulator stations from high-pressure ($P \geq 980$ kN/m^2) transmission lines. Hence, emergency operations can be conducted for each K-block without affecting other K-blocks. The first stage operation is a blockage of each K-block, which means to shut off valves of medium-pressure lines at K-block boundaries. This operation has no significant effect on the gas supply. Thus, this operation is carried out if telemetered SI values exceed 25 cm/s in at least two locations for each K-block.

The second stage operation is the shutoff of gas supply within a K-block by closing regulators of medium-pressure lines. After that, medium-pressure gas may be released to the air from dispersion towers, if necessary. However, once this shutoff is carried out, its effects are tremendous and recovery may take a long time. Thus, this decision must be conducted carefully. Hence an extensive earthquake monitoring system has been developed.

The primary items of the monitoring are the spectrum intensity (SI) and the peak ground acceleration (PGA) at 331 points within the service area by SI-sensors (Katayama et al., 1988). Three sensors are laid for each L-block (about 10 L-blocks in each K-block). Once an earthquake occurs, monitored SI and PGA values will be transmitted to the headquarters by radio and damage estimation will be conducted. The SI is used as the primary index of damage estimation since it has been shown to have higher correlation with damage due to earthquakes than other indices (Iwata et al., 1992; Yamazaki et al., 1994b).

Acceleration time histories at 5 locations are also monitored (Figure 1). These stations are located near the outer edge of the service area. The radio-transmitted records are used to determine the magnitude and focus of an earthquake within a few minutes. Newly developed liquefaction sensors are also laid at 20 locations in the service area to detect the occurrence of liquefaction. Measured pore-water rises by three levels are also sent to the control center by radio.

Installation of all the earthquake monitors and expansion of radio system were completed in early 1994 and actual operation has started.

Early Warning System

In order to assist in the decision making on gas supply shutoff, an early warning system (SIGNAL) based on the monitoring has been developed and has started operating since June, 1994. Figure 2 shows the flowchart of the system, which consists of four sub-systems: damage estimation, hypocenter estimation, spectrum evaluation, and decision.

SIGNAL was developed on an engineering workstation using a Geographic Information System (GIS). Since earthquake

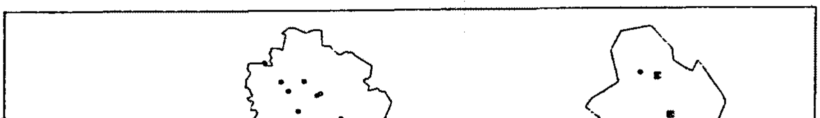

Figure 1. Earthquake monitors of Tokyo Gas

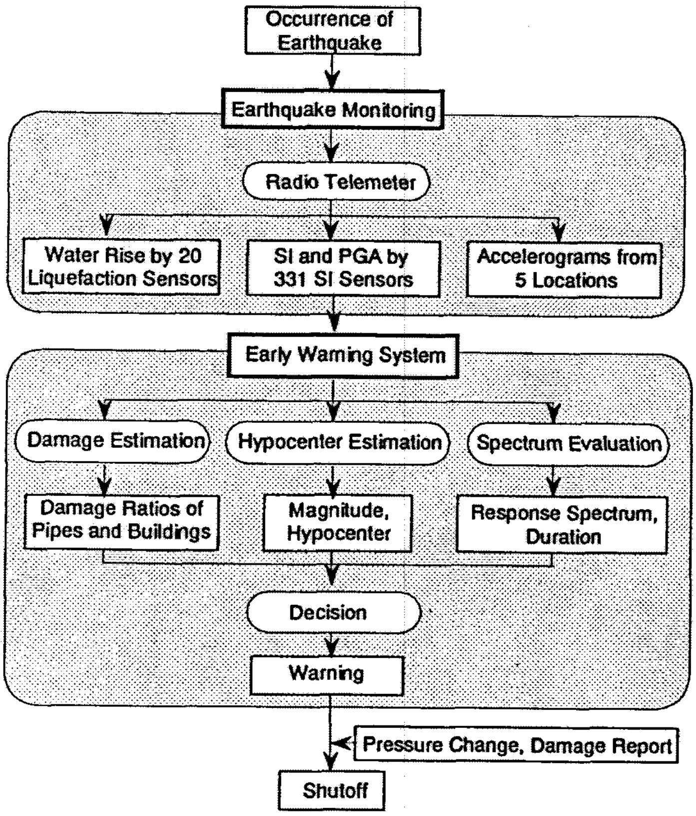

Figure 2. Flowchart of SIGNAL

ground motion is highly influenced by soil conditions, micro-zoning of the service area with mesh size of 250m x 175m was carried out. The micro-zoning used standard penetration test data, which were widely collected for the area. Soil condition of each subzone is represented by four soil categories (3 for lowland and 1 for highland) based on local topography and estimated predominant period of surface layers. The measured values of the nearest SI sensor on the same soil category are considered to represent ground motion of each subzone. A table which relates the SI value and the thickness of liquefied soil layer is also prepared for each subzone. As an example, Figure 3 shows K1 and K2 blocks (Central Tokyo) with the layout of SI sensors and local topography.

GIS data for customers' buildings and gas pipelines are also prepared for the same subzones. The lengths of pipelines are stored for different pressure levels (medium or low), materials and diameters. For customers' buildings, number of customers within each mesh is prepared.

In the damage estimation, damage ratios of customers' buildings and pipelines within each subzone are calculated based on empirical relationships developed for recent earthquakes in Japan (Tong et al., 1995). The thickness

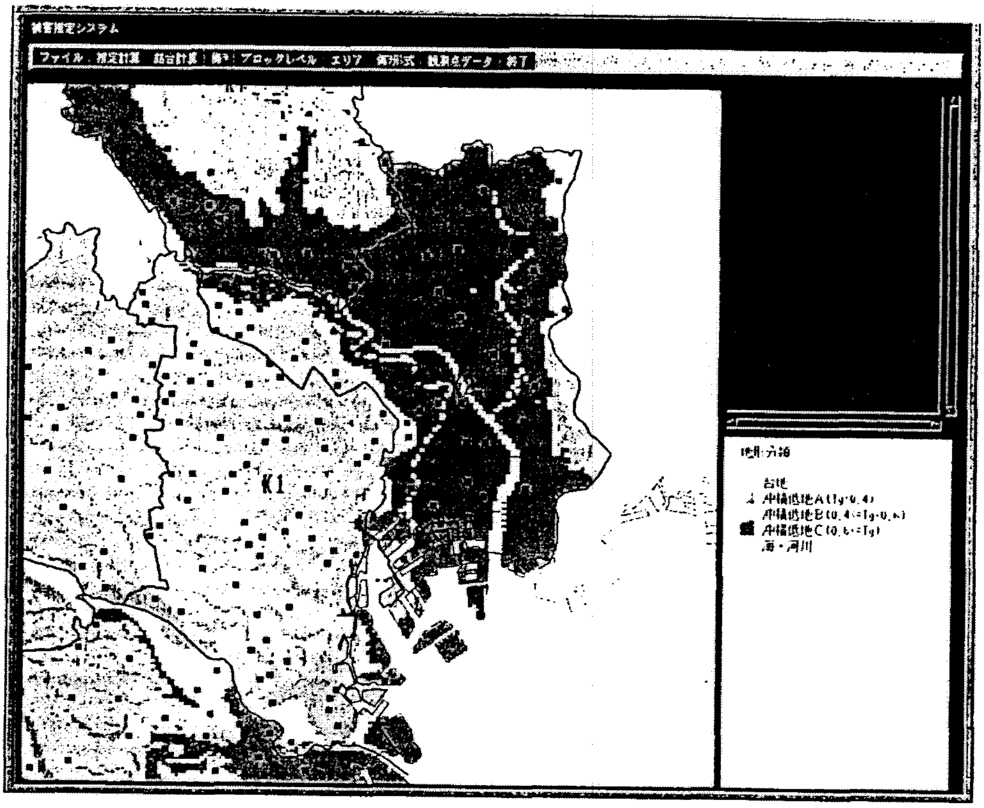

Figure 3. Local topography and sensors in the two blocks

of the liquefied sand layer is considered to modify the damage ratios. The damage ratios of a K-block are then obtained by taking weighted averages for those of the subzones. The weight for each subzone is determined by the number of buildings or the total length of pipelines within the subzone.

The hypocenter estimation system calculates the JMA (Japan Meteorological Agency) magnitude and the hypocenter (location and depth) of an event using the time lags between the P-wave and S-wave arrivals (Noda and Kano, 1993). This sub-system estimates the hypocenter and the magnitude within a few minutes after receiving acceleration time histories from the five locations.

The spectrum evaluation system calculates the acceleration response spectra and durations of the records from the five locations. These values are then compared with those from past damaging events. The spectral characteristics may indicate the dominant period of structures which might have been damaged.

The decision system uses the estimated results from the three sub-systems. The average damage ratios of buildings and pipes in each K-block, obtained by the damage estimation system, are used for the primary decision making. Since, we have two damage ratios with different units (% for buildings and no./km for pipelines), the problem becomes a decision analysis with two variables and two alternatives. Two-variable utility functions (Cret et al., 1993) must be prepared to carry out this decision making. Two-dimensional utility functions for the two alternatives, maintain or cut the gas supply, must be prepared for this purpose based on a cost evaluation or experts' opinion, although it is not an easy task. The results from the hypocenter estimation system and the spectrum evaluation system are further considered in the secondary decision making.

Case Studies

After installation of SIGNAL, case studies were conducted for the hypocenter estimation and damage estimation sub-systems. Figure 4 shows the comparison of epicenters estimated by SIGNAL and JMA for actual earthquakes. For most cases, epicenters estimated by SIGNAL are close to those by JMA as well as depths and magnitudes. For some cases, discrepancy is observed. However, those are the cases with very small recorded accelerations or far events.

The damage estimation sub-system of SIGNAL was examined using scenario earthquakes. Figure 5 shows the damage ratio of buried pipes for each subzone due to a scenario earthquake, which simulates the 1855 Ansei-Edo Earthquake. The hypocenter is located at a reclaimed land of Tokyo Bay with a depth of 20 km and JMA magnitude of 7.0. A total of 12 breaks was estimated for medium-pressure lines and over five thousand breaks for low-pressure lines. Concentration of pipe breaks is seen in Tokyo lowland and waterfront areas, where extensive liquefaction is expected.

Concluding Remarks

This paper describes an early warning system of the largest city gas network in Japan based on extensive earthquake monitoring. Since the service area of the natural gas system became very large, the earthquake monitoring and early warning system was introduced to avoid secondary disasters. The monitoring system measures the PGA and SI values at 331 locations in the service area. 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 by radio and are used in decision making on the gas supply shutoff.

The early warning system consists of sub-systems for

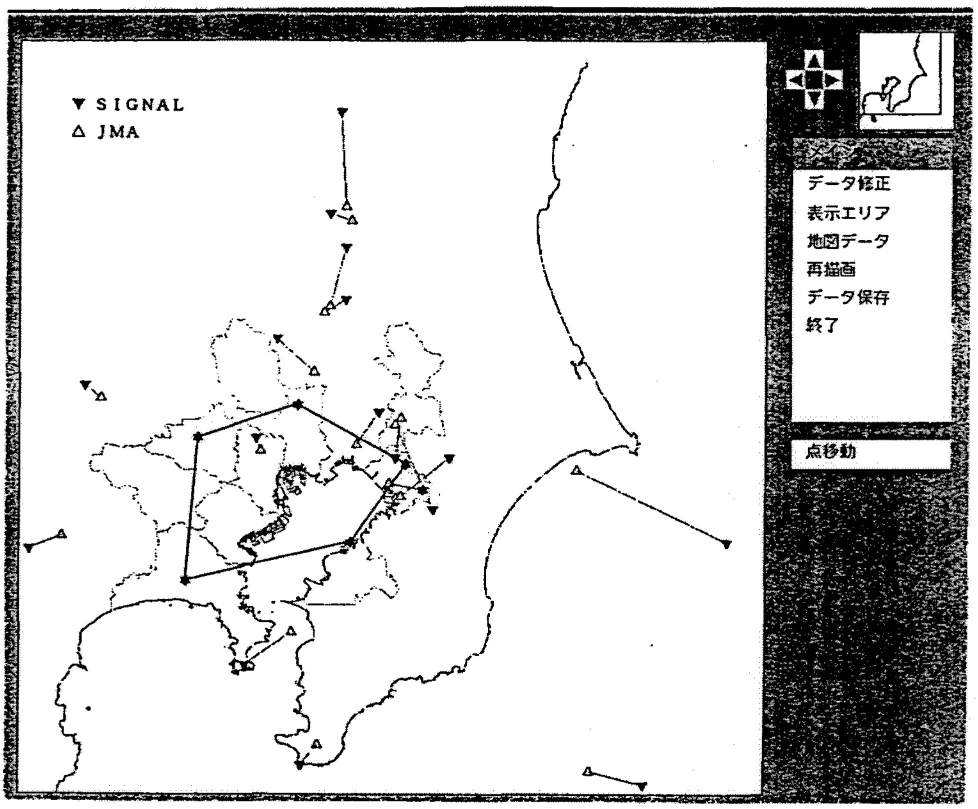

Figure 4. Epicenters estimated by SIGNAL and JMA

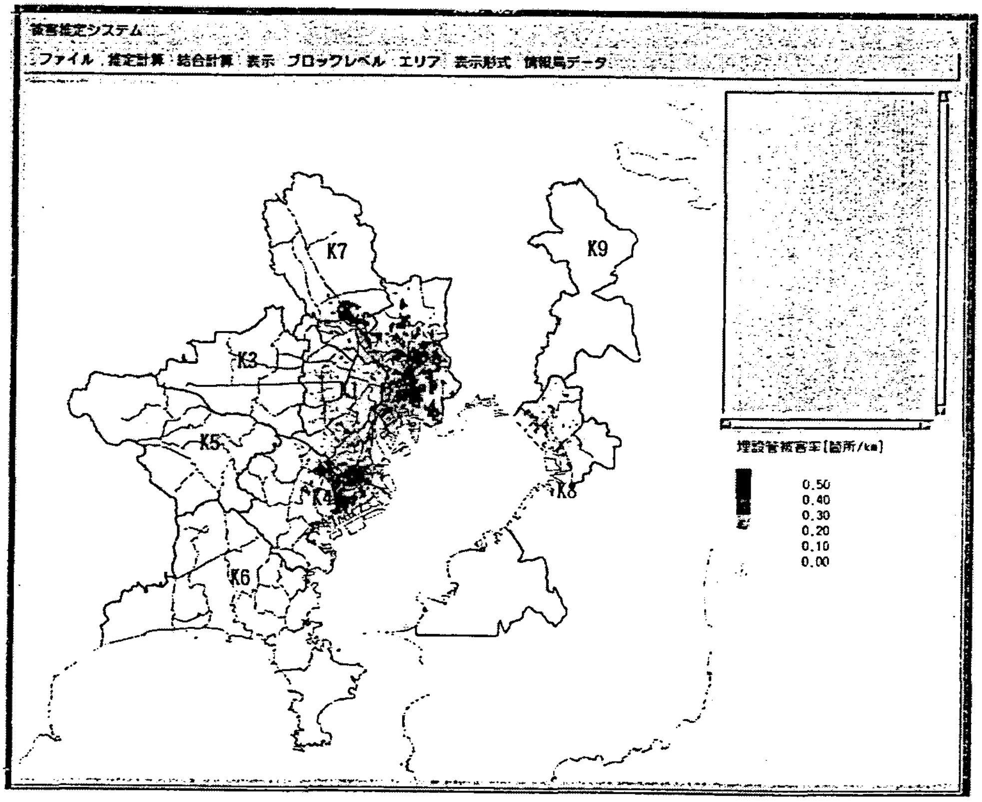

Figure 5. Damage ratio of pipes for scenario earthquake

damage estimation, hypocenter estimation, spectrum evaluation, and decision. The monitored earthquake groundmotion data are fully employed in these 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. The actual system started its operation in 1994. Case studies were provided using actual records for hypocenter estimation and using scenario earthquakes for damage estimation.

Although the framework of the early warning system has been completed, further revision may be necessary for the damage estimation relationships to consider recent damaging earthquakes, notably the Great Hanshin Earthquake. Installation of the spectrum evaluation and decision systems is another remaining task.

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