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CONSTRUCTION AND USE OF EARTHQUAKE DAMAGE ESTIMATION SYSTEM FOR CITY GAS SUPPLY SYSTEM

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ABSTRACT

In Japan, the frequent occurrence of large-scale earthquakes creates the need for earthquake disaster prevention systems that focus on gathering damage information on gas supply facilities immediately after an earthquake strikes and minimizing the damage.
The authors constructed an earthquake damage estimation system for city gas pipelines that can show damage information in real-time by using earthquake records obtained from densely deployed earthquake observation networks and the most advanced telecommunication and information technologies.
This system can be used to estimate damage during an emergency and in normal times and has database management functions.
During an emergency, it acts as an on-line damage estimation system using observed values obtained from earthquake observation systems immediately after an earthquake and it provides various damage estimates such as the distribution of earthquake motion, the outbreak of liquefaction, and the damage status of city gas pipelines.
In normal times, this system can simulate earthquake motions taking into consideration both maritime trench earthquake models and active faults, and can predict damage by using such simulation.
This article summarizes the Earthquake Damage Estimation System and Toho Gas disaster prevention measures.

1. Introduction

Ensuring a stable, secure supply of city gas is a crucial mission entrusted to a gas company. Everyday, Toho Gas puts every effort into this mission. The experience of the January 1995 Magnitude 7.3 Hyogo-Ken Nambu (Kobe) earthquake reminded Japan and city gas companies of the importance of countermeasures for earthquakes. Japan, which is particularly prone to earthquakes, is subject not only to inland near-field earthquakes, such as the Hyogo-Ken Nambu earthquake, but must also concern itself with maritime trench earthquakes occurring at underground tectonic plate boundaries. The Tokai, Tonankai, and Nankai earthquakes forecast to

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occur in the near future are maritime trench earthquakes forecast to exceed Magnitude 8. As Fig. 1 shows, they have occurred repeatedly in the past with cycles of 80 to 150 years. Such major earthquakes will have unavoidable impacts on Toho Gas's supply area, so Toho Gas is moving rapidly on countermeasures.

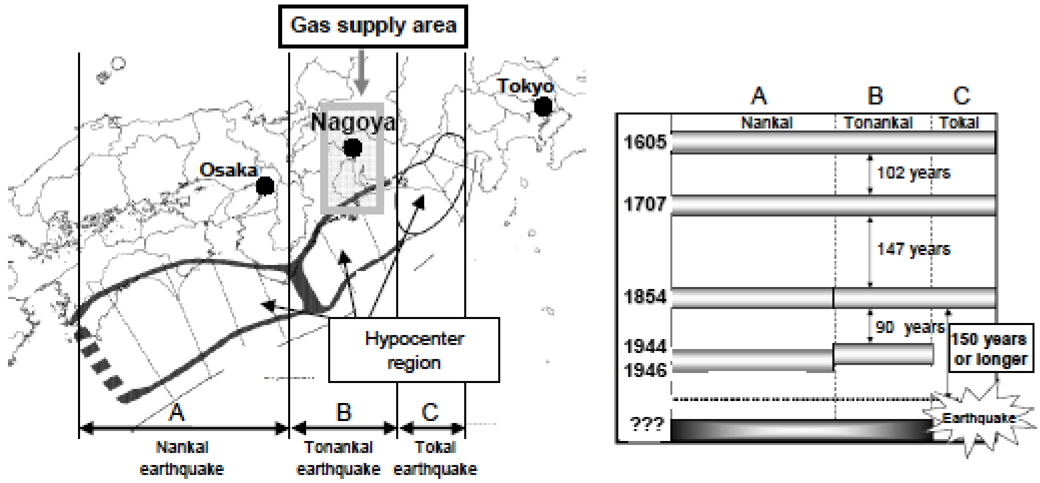


Figure 1. Tokai, Tonankai, and Nankai earthquake assumed hypocenter area (left) and earthquake occurrence history (right).

Given this, Toho Gas is devoting itself not only into countermeasures to enable our gas supply facilities to better withstand earthquakes, but also emergency countermeasures for when an earthquake occurs. As emergency countermeasures, it is necessary to construct an earthquake disaster prevention system that can quickly determine the damage status of gas supply facilities and minimize the post-earthquake disaster. Toho Gas has constructed and put into use an "Earthquake Damage Estimation System" utilizing the concept of real-time post-earthquake disaster prevention. This paper summarizes this "Earthquake Damage Estimation System" and introduces the current state of Toho Gas's earthquake countermeasures for city gas supplies.

2. Toho Gas's City Gas Supply Method and Current State of Earthquake Countermeasures

2-1. Toho Gas Supply Method

Toho Gas supplies city gas to the city of Nagoya and the surrounding area, which are in the central region of Japan. Toho Gas serves approximately 2.225 million customers and has a total length of approximately 26,000 km of city gas pipes (as of March 2009). As Fig. 2 shows, Toho Gas supplies city gas at four levels of usage pressure. City gas is produced at Toho Gas gas plants from liquefied natural gas (LNG) imported from natural gas producing nations. This city gas is first sent out at high pressure (greater than 1.0 MPa). Then, at each critical point, governors reduce the pressure to Medium A pressure (0.3 to 1.0 MPa), Medium B pressure (0.1 to 0.3 MPa), then low pressure (about 2.5 kPa) to supply it to customers.

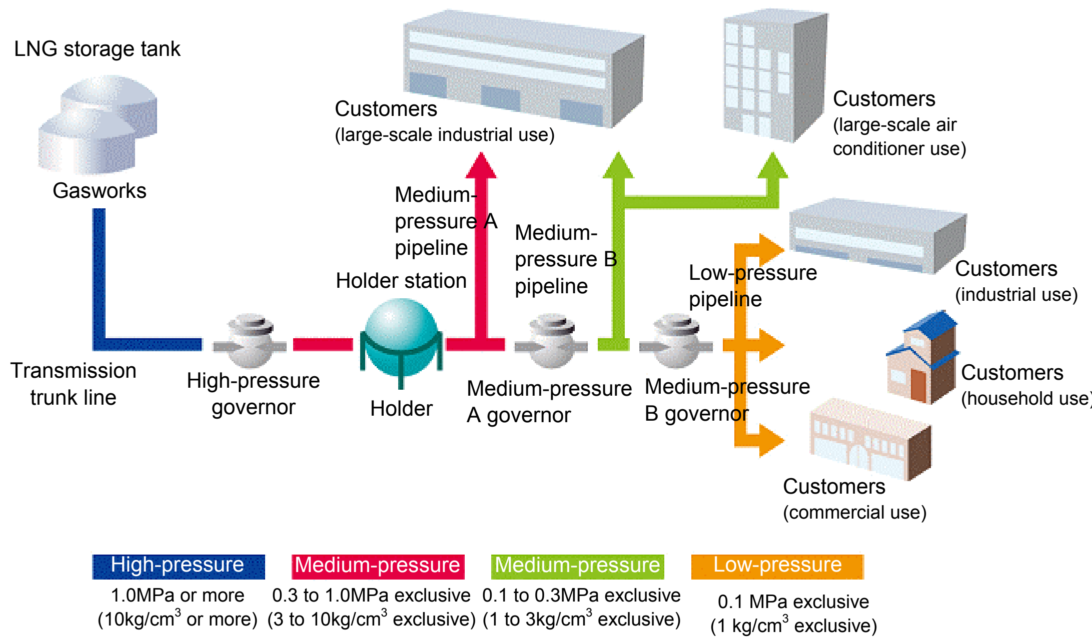


Figure 2. Toho Gas city gas supply system.

2-2. Earthquake Countermeasures

Table 1 shows some of the many ways Toho Gas has strengthened its earthquake countermeasures since the Hyogo-Ken Nambu earthquake.

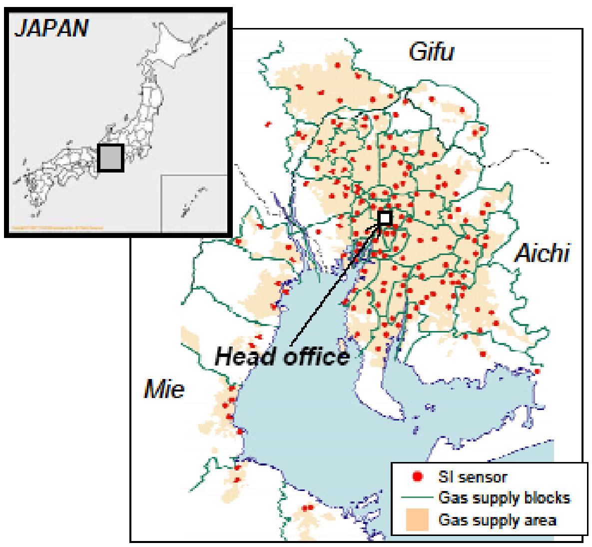
Table 1. Progress of main earthquake countermeasures.

Earthquake countermeasures (partial)	1995	2009
Polyethylene pipe proportion (low-pressure gas pipes)	Approx. 5%	Approx. 39%
Number of gas supply blocks	8 blocks	50 blocks
Number of seismographs (spectral intensity sensors) installed	55	180
Number of remote pressure and flow monitoring and control units installed	108	308
Microprocessor-based meter installation (for homes)	Installation underway	100% installation

First of all, the ability of gas supply facilities to withstand earthquakes has been improved. As an example, Toho Gas is spreading and expanding its use of polyethylene pipes, which suffered absolutely no damage even in previous major earthquakes, for low-pressure gas pipes. Toho Gas is also vigorously implementing measures to increase the ability of other gas supply facilities to withstand earthquakes.

Secondly, Toho Gas is forming its pipe network into blocks. At the present time, Toho Gas has divided its gas supply area into 50 blocks (Fig. 3). Shut-off valves at the boundaries between blocks are normally kept closed to divide the pipe network into blocks. When a disaster strikes, this block system forcibly stops the supply of gas to any blocks with severe damage. This has the advantages of preventing secondary disasters due to gas leaks, fires, etc. and making it possible to minimize the area in which gas supply is stopped.

The judgment whether or not to stop gas supplies uses spectral intensity (SI) sensors. SI sensors are installed at multiple locations in each block (180 locations in total (Fig. 3)) and when an SI value of more than 60 kine is recorded, the gas supply for that block is stopped remotely. Fig. 4 shows the method for stopping. This method stops the medium pressure A governor for the target block remotely to stop the supply of gas with medium pressure B or lower.



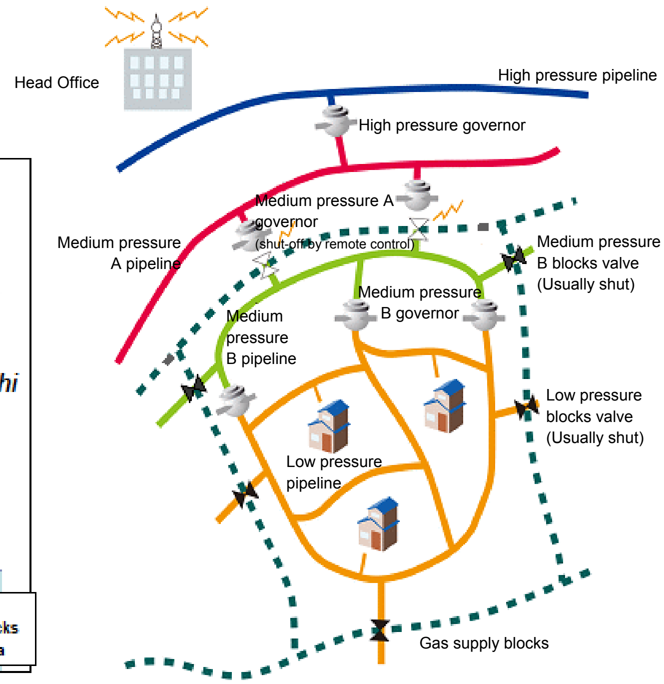


Figure 3. SI sensors and gas supply blocks.

Figure 4. Blocking off of gas supply.

Toho Gas not only uses remote operation to stop the supply of gas, but also remotely monitors and controls gas pressure and flow at key points from its head office. Currently, more than 300 points are remotely monitored and controlled.

One of the other measures, Toho Gas is taking is to spread and expand the use of microprocessor-based meters. A microprocessor-based meter is a meter that has functions for detecting earthquake motion and any gas leaks that occur at a customer's site and for automatically shutting off the gas supply. Currently, Toho Gas has spread such meters to nearly 100% of its customers, including 100% of the residential customers.

2-3. Construction of Computer Systems

In order to able the quick determination of the damage status of gas supply facilities after an earthquake, Toho Gas is constructing various computer systems. Fig. 5 summarizes these systems.

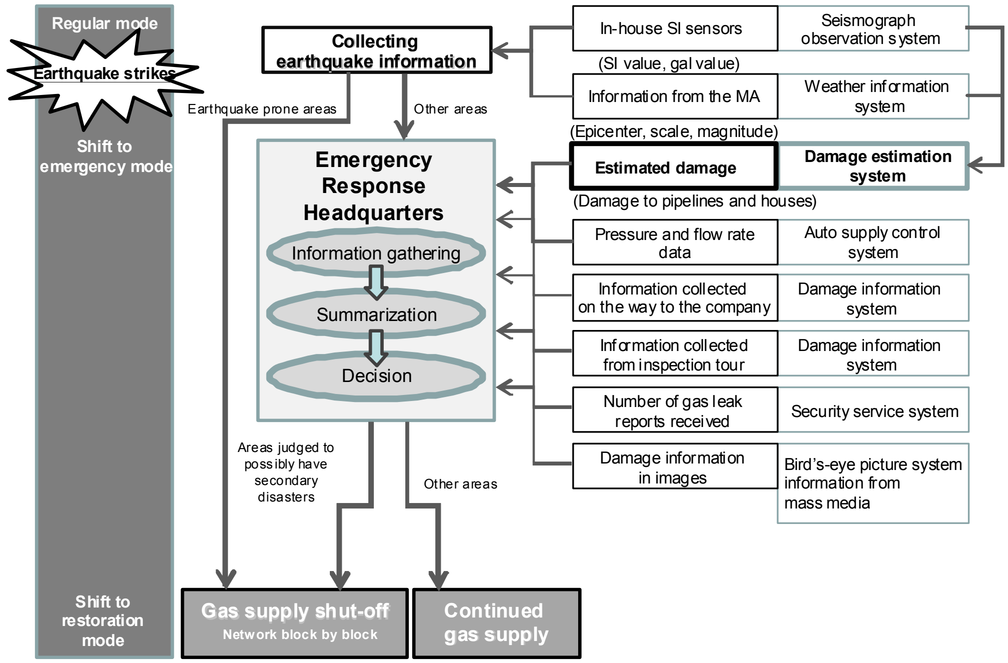


Figure 5. Systems for determining damage status.

The "Seismograph observation system" makes it possible to centrally manage over 180 seismographs (SI sensors) from the company head office. The resulting observation data is used not only in the gas supply shut-off judgment discussed above but also serves as the basic data for the "Earthquake damage estimation system" discussed below.

Toho Gas's systems also include the following three systems. The "Weather information system" provides such information as the earthquake hypocenter, scale, and magnitude immediately after an earthquake. The "Auto supply control (SCADA) system" remotely monitors and controls gas flow and pressure and can stop gas supply remotely. The "Security service system" sends leak reports from customers to radio-equipped repair service cars.

3. Earthquake Damage Estimation System

The main objective of the "Earthquake damage estimation system" is to estimate the damage to low-pressure gas pipes and service pipes. Fig. 6 summarizes this system, which can be divided into three main functions. The first function is the "emergency" damage estimation function. The second function is the simulation function for "normal operations". The third function is the database management function. This function makes it possible to update and correct the numbers and map data used in the damage estimation system and protects the system from becoming out-of-date.

The results of the damage estimation can be displayed as a surface mesh that covers the Toho Gas supply area with approximately 540,000 units (125x167 m). This system also has functions for organizing and displaying data by blocks and by administrative districts.

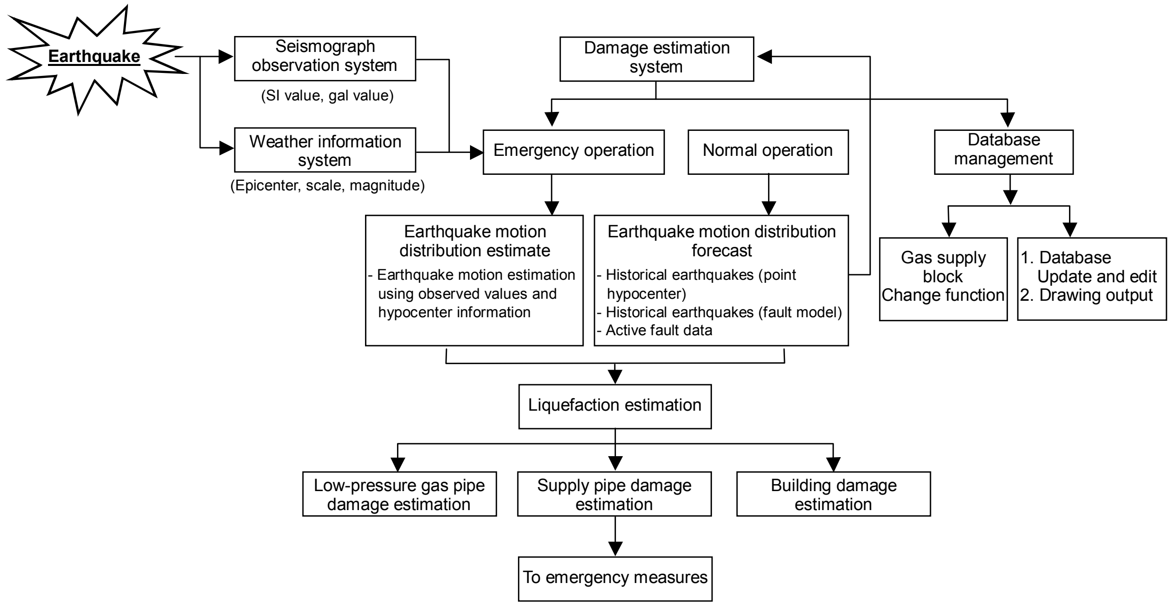


Figure 6. Summary of earthquake damage estimation system.

Below is a summary of the damage estimation procedures for "emergency operation" and "normal operation".

3-1. Emergency operation

In an emergency, this system collects the SI values and peak ground acceleration for each seismograph observation point, epicenter position and hypocenter depth and the Meteorological Agency magnitude information from the "Seismograph observation system" and the "Weather information system". Using this earthquake information, this system estimates the earthquake motion distribution and various forms of damage.

The results of emergency damage estimation are used to decide what to do, for example to judge whether to stop the gas supply for each block, to plan inspection tours of gas supply facilities, to estimate the volume of the equipment and staff required in the restoration phase, and to forecast the time until restoration is complete.

First, in the earthquake motion distribution estimation, the SI value and peak ground acceleration are estimated for each mesh unit using the observed seismograph values and the hypocenter information. The relation between the observed values and the estimated values, which are evaluated based on the ground amplitude and the attenuation equations for earthquake response spectra [1), 2)] using the hypocenter information, is interpolated by the technique called Kriging. Using their method, the earthquake motion distribution of other points is estimated. In this way, at the observation points, the observed seismograph data is treated as the true values and at other points, the accuracy of estimates is improved by taking into account the distance attenuation effect and the amplitude characteristics of earthquake motion. Also, even if observed seismograph values or hypocenter information are unavailable, earthquake motion can be forecast from this data using interpolation and the distance attenuation equations.

After estimating the earthquake motion distribution, this system forecasts the occurrence of liquefaction using the P_L method [3]. First, the microtopographical data is used to focus in on the liquefaction region. Then this system uses the database of P_L values constructed for the entire gas supply area and the results of peak ground acceleration estimation to forecast liquefaction. Referencing previous research, the criterion used is that if the P_L value < 15, it is judged that there is no liquefaction and if the P_L value ≥ 15, it is judged that there is [3].

Next, this system estimates the damage to low-pressure gas pipes, service pipes, and wooden buildings. Damage to low-pressure gas pipes is estimated for thread-coupled steel pipes and ductile cast iron pipes. (Polyethylene pipes are calculated as having no damage.) The damage estimation equations (1) and (2) used for estimating damage have been newly constructed by restudying the damage data for eight earthquakes in various parts of Japan (1968-1995) including with the Hyogo-Ken Nambu earthquake of January 1995.

Here, D_{LP} is the damage rate (incidents/km) for low-pressure gas pipe, C_P is the pipe type correction coefficient, C_g is the ground correction coefficient, C_l is the liquefaction correction coefficient, and C_d is the reclaimed land correction coefficient. Table 2 shows details. R_{LP} is the reference damage rate (incidents/km) for low-pressure gas pipe. This can be expressed as a function of the SI value as in Fig. 7.

$$D_{LP} = C_p \cdot C_g \cdot C_l \cdot C_d \cdot R_{LP} \quad (1)$$

$$R_{LP} = \begin{cases} 0.0 & (SI \leq 25) \\ 3.5 \times 10^{-2}\left(SI - 25\right)^{0.97} & (25 < SI \leq 80) \\ 1.7 & (SI > 80) \end{cases} \quad (2)$$

Table 2. Correction coefficients.

Pipe type correction coefficients

Pipe type	C_p
Thread-coupled steel pipe	1.0
Ductile cast iron pipe	0.4

Ground correction coefficients

Microtopographical name	C_g
Mountainous district, plateau land, benches	1.0
Slight elevation in low land	1.6
General level of low land	1.2
Artificial ground	1.7
Reclaimed/liquefaction ground	1.0

Liquefaction correction coefficients

Reclaimed/liquefaction ground	C_l
Alluvial stratum thickness 0 m to 4 m	1.3
Alluvial stratum thickness 4 m to 8 m	2.7
Alluvial stratum thickness 8 m to 12 m	3.5
Alluvial stratum thickness 12 m ～	3.9

Reclaimed ground correction coefficients

Fill-up ground characteristics	C_d
Earth cut	1.6
Embankment or pond fill-in	2.6
Cut and fill unknown	1.9

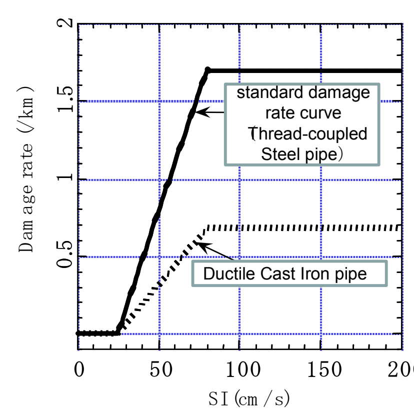


Figure 7. Low-pressure gas pipe damage evaluation curves.

The damage estimation system also estimates the damage to gas service pipes and the damage to wooden buildings. This is crucial information for supporting more accurate judgment of when to stop gas supplies.

3-2. Normal Operation

The system has the historical earthquake fault model and active fault hypocenter information database constructed for the area within about 200 km of the Toho Gas's gas supply area. In addition, an earthquake motion estimation equation was constructed by statistically processing the relationship between earthquake ground motion and hypocenter information. Using this method, the earthquake motion distribution is estimated. Based on these earthquake motion distributions, the damage to low-pressure gas pipes, service pipes, etc. is estimated. (The damage estimation technique is the same as for emergencies.)

Table 3 summarizes the hypocenter information that can be used at the current stage and Fig. 8 shows part of the hypocenter information.

Table 3. Hypcenter information database summary.

Type	Hypocenter model	Details	Selection criterion
Historical earthquakes	Point hypocenter model	21 earthquakes including Meio Era Tokai earthquake	Within 200 km of supply area and peak base-rock acceleration hypothesized for supply area has minimum value of 50 cm/s^2 and higher
	Fault model	25 faults including Tonankai earthquake	Main items within 200 km of supply area
Active fault	Fault model	63 faults including Ise Bay fault	Within 200 km of supply area and maximum ground acceleration hypothesized for supply area has minimum value of 50 cm/s^2 and higher

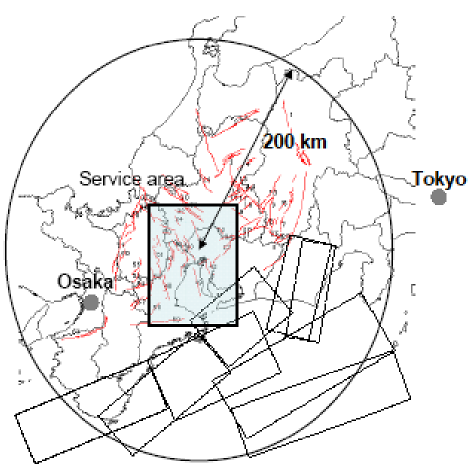


Figure 8. Part of hypocenter information database.

Using the functions for normal operation, Toho Gas proposes future concepts for earthquake resistance measures for gas supply facilities and reviews gas supply blocks. These functions also provide the foundational data for company-wide disaster prevention training for hypothetical disasters. Toho Gas is using this analytic data to move forward with preparations for the various major earthquakes that are seen as possibly occurring in the future.

4. Verification of Functions in Actual Earthquakes

In July 2007, a magnitude 6.8 earthquake occurred in Niigata Prefecture. This earthquake caused the stopping of the supply of gas to 34,000 customers. Restoration required 42 days. Toho Gas also sent crews to support service restoration activities.

The data on damage to gas pipes from this earthquake was used to verify the accuracy of Toho Gas's earthquake damage estimation system. The verification method was to obtain gas pipe damage data, pipe diagrams, ground data for the surroundings, and detailed earthquake motion data, plug this data into Toho Gas's earthquake damage estimation system, and compare the results of these calculations against the actual damage values.

Although the calculated values were slightly less than the actual values for both the number of damage cases and the damage rate, as Table 4 shows, the results obtained were generally good.

Table 4. Comparison of by damage estimation calculations against actual values.

Pipe type	Total length (km)	Damage cases (cases)		Damage rate (cases/km)	
		Calculated value	Actual value	Calculated value	Actual value
All pipe types	13.592	29.0	40	2.24	2.94
Threaded steel pipe	6.648	21.7	28	3.37	4.21

Two points can be given as the reason for the divergence of the calculated values from the actual values.

The first point concerns the diameter of the gas pipes. It is generally held that the damage rate is higher for small-diameter gas pipes, but the current system has no correction coefficient set for the pipe diameter. In the Niigata region earthquake used for verifying the system, a comparatively large proportion of the pipe consisted of small-bore pipe, so the calculated values did not match the actual values. The second point is that it is conceivable that the error increased because the density of total gas pipe length in each mesh unit analyzed was comparatively low. It was confirmed that when only mesh units were analyzed that had a total length of at least 300 m of pipe, the match between the calculated values and the actual values improved.

In this way, a variety of future actual earthquake data and damage data will be used to revise the damage estimation equations and to improve the accuracy of damage estimates.

5. Summary

This paper summarized Toho Gas's earthquake countermeasures and introduced the basic functions of the "Earthquake Damage Estimation System" utilizing the concept of real-time post-earthquake disaster prevention. Here is a summary of the features of this system.

- When there is an emergency, this system functions as an online system using seismograph observation data and hypocenter information and estimates the earthquake motion distribution, liquefaction distribution, and the damage to low-pressure gas pipes, service pipes, and wooden buildings.
- During normal operation, earthquake motion can be estimated taking into account historical earthquakes and active faults and any desired earthquake data can be inputted, so a wide variety of damage estimation simulations are run.

Finally, two issues for the future can be raised.

(1) Improving the accuracy of damage estimation equations
Gas pipe damage from actual earthquakes, such as the Niigata Prefecture earthquake discussed earlier and the Magnitude 6.5 earthquake that occurred offshore from Shizuoka Prefecture in August 2009, will be analyzed and the accuracy of the system improved.

(2) Response to marine trench earthquake long-period ground motion and long-prolonged ground motion
The current damage estimation equation was created primarily using data for inland near-field earthquakes. The hypothetical damage for the Magnitude 8 class marine trench earthquake forecast to occur in the near future in this region will be researched and new damage estimation equations constructed.

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