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DEVELOPMENT OF EARTHQUAKE RESISTANCE EVALUATION METHOD FOR BURIED PIPELINE NETWORKS

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SUMMARY

A new method is developed for evaluation of earthquake resistance of buried pipelines.
The seismic resistance of buried pipeline was conventionally evaluated only by the strength of material used for the pipeline. Consequently, the buried pipeline with weak-strength material was recognized as the pipe to be replaced or to be reinforced. Therefore, the conventional method could be over-investment if it is used for the determination of replacement / reinforcement plan.
Here, it is obviously important to develop the new seismic resistance evaluation method for buried pipes where both the soil conditions and the network shapes are taken into consideration, in order to make the replacement / reinforcement plan to be effective.
In this new method, the seismic resistance of the buried pipes can be evaluated reasonably through comparison between the strength of the buried pipes and the external forces on the pipes induced by design earthquake motion.

Outline of the New Evaluation Method

In this new method, the seismic resistance of the buried pipes can be evaluated reasonably through comparison between the strength of the buried pipes and the external forces on the pipes induced by design earthquake motion, as shown in Fig.1.
Here, SUPREME[1)] (**Sup**er High Density **Re**al-time **M**onitoring of **E**arthquakes) is the real-time city gas damage mitigation system which has been developed by Tokyo Gas and in operation at Tokyo metropolitan area since July, 2001. SUPREME has detailed GIS database such as 60,000 bore-hole logging data, geological classification data and 48,000km – length pipeline data. In addition, the "Seismic Design Guideline for High Pressure Gas Pipeline"[2)] was published in 2000 and the "Seismic Design Guideline for High Pressure Gas Pipeline Buried in Liquefiable Soil Areas"[3)] was set in 2001. Utilizing these guidelines and SUPREME database, the external forces on the buried pipes can be accurately calculated. Moreover, a fast analytical method for seismic responses of buried pipeline networks[4)] has

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been newly developed. Utilizing this method and the strength database obtained by experiments, the strength of the buried pipeline can be accurately calculated.

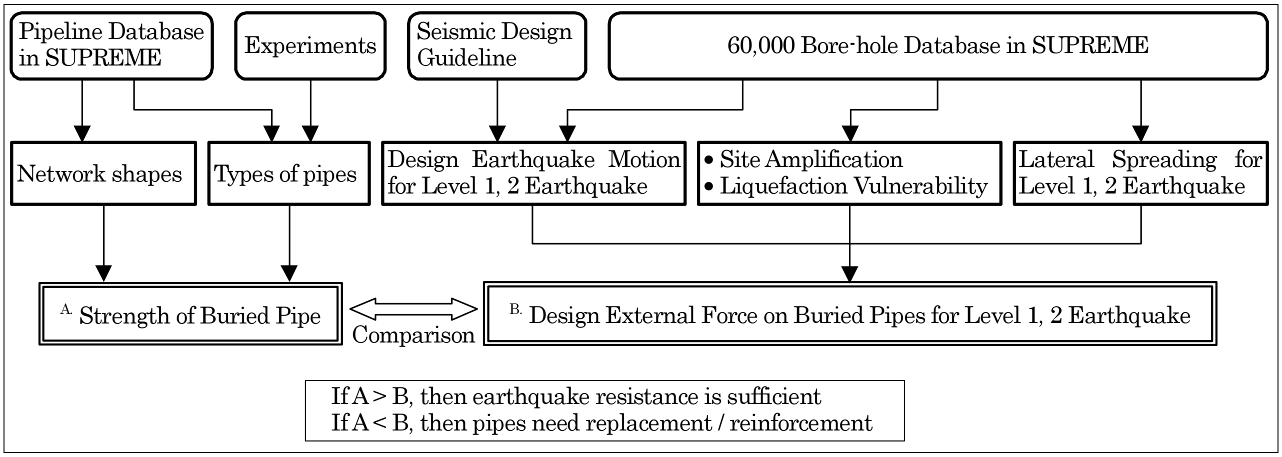

Fig.1: Basic Concept of the New Method

Design External Force

The design external force can be assumed according to any seismic design guidelines. Here, for the example, the procedure to calculate the external force induced by "Shaking" based on the "Seismic Design Guideline for High-Pressure Gas Pipeline" is introduced.

According to the "Seismic Design Guideline for High-Pressure Gas Pipeline", the velocity response spectrum at the engineering baserock is defined as shown in Fig.2, respectively for Level 1 and 2 Earthquakes. The level 2 Earthquake based on the acceleration waveform of 16 of the southern Hyogo earthquake. It depends for response speed on the natural period of the foundation greatly so that more clearly from Fig2.

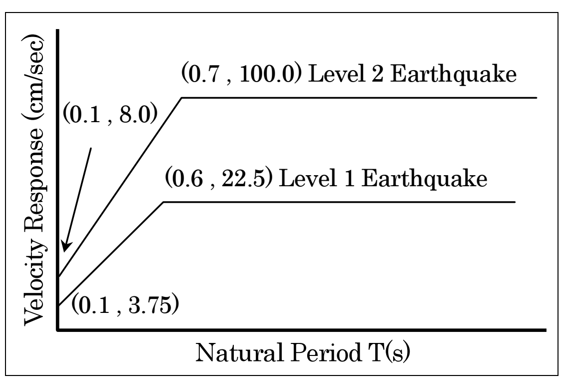

Fig.2: Velocity Response Spectrum for Level 1 and 2 Earthquake[2)]

In SUPREME, the natural period database is prepared on GIS with 50m×50m pixels as shown in Fig.3, utilizing a total of 60,000 borehole logging data (Fig.4).

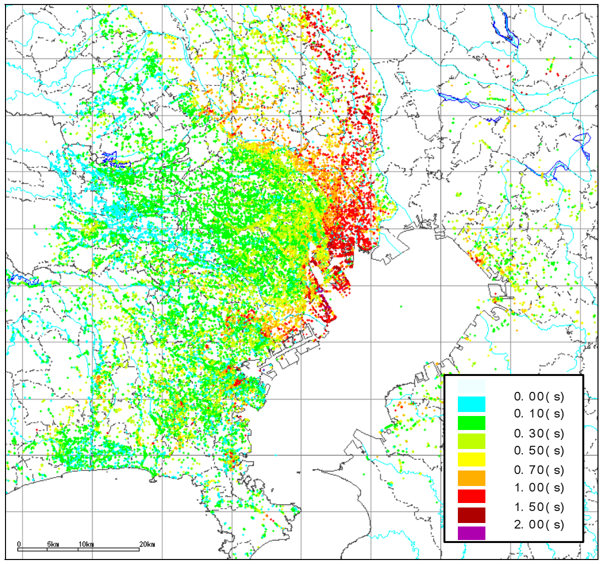

Fig.3: Natural Period Database in SUPREME

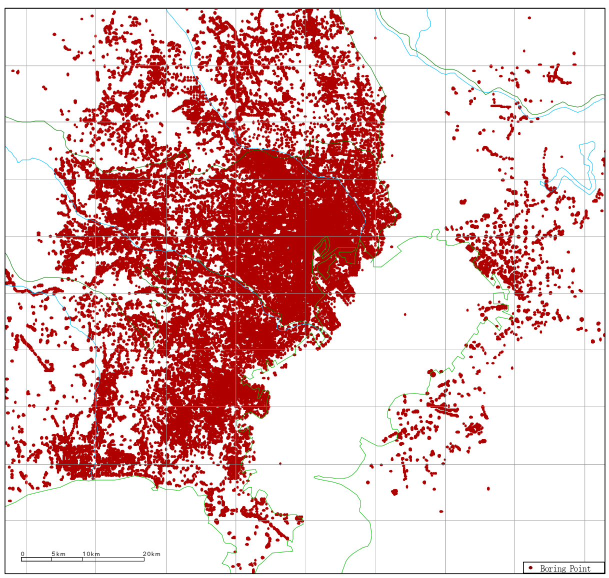
Fig.4: Sites of bore-holes employed in SUPREME.

Based on Fig.2 and Fig.3, the velocity response on the engineering baserock at any points can be estimated. Then, utilizing the design guideline, the external forces or the strain of the buried pipe may be of course calculated. Here, to make the procedure as simple as possible, the design external forces is expressed as design SI values at any points on the surface ground. The SI value on the engineering rock (SI_B) can be expressed by Eq.1.

$$SI_B = 1.18 \times Sv \qquad \text{(Eq.1)}$$

The conversion factor from the engineering rock to surface for SI values was defined in the guideline as 4/ π .
Then the design SI values on the surface ground (SI_S) can be obtained by Eq.2.

$$SI_S = \frac{4}{\pi} \times SI_B \quad \text{(Eq.2)}$$

Strength of the Buried Pipe

Strength Database Obtained by Experiments

Tokyo Gas's medium pressure pipeline networks contains welded steel pipes, ductile cast iron pipes, welded steel valves, ductile cast iron valves and cast iron valves. For all these elements, the compression and tensile strength data were obtained through vast volume of experiments.

For example, the results of tensile strength tests for cast-iron valves with different diameters are shown in Fig.5, Photo.1 and Table.1.

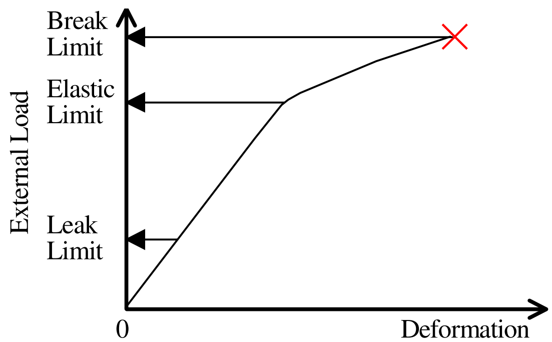

Fig.5: Tensile Strength Tests for Cast Iron Valves

Photo.1: Tensile Strength Tests for Cast Iron Valves

Table.1: Tensile Strength of Cast Iron Valves

Diameter (mm)	100	200	300	600
Elastic Limit (tf)	26	35	39	188
Break Limit (tf)	46	72	136	439

Here, 3 tensile strengths are defined as follows. "Leak Limit" is the tensile strength where leakage starts to occur at the flange joint. "Elastic Limit" is the tensile strength where plastic deformation starts to occur.

“Break Limit” is the tensile straight where valves break. These strength data has been used for selection of valves to be replaced or reinforced and determination of priority.

Development of NeEX

The maximum strain or the maximum axial force induced by “Shaking” depends on the ground surface deformation (Uh) and the network shapes. The exact answer can be obtained if FEM calculation is conducted for vast spatial pipeline network but the calculation volume will be too large to be practical (Fig.6). Then. the fast analytical method for seismic responses of buried pipeline networks, namely NeEX[4)], has been developed to reduce the calculation volume. In this method, to neglect the effect of distant pipe, the network is divided into many small pipe elements which contain a straight pipe and boundary elements such as bend, as shown in Fig.7. If FEM calculation is conducted for all these small elements, the calculation volume cannot be reduced. Then, in advance, the strength database such as “stress-strain curve” is prepared for each boundary elements such as bends or Tees, by using FEM calculation results or experiment results. Then, for each small pipe element, non-linear equation with a condition of force equilibrium and deformation consistency will be solved (Fig.8). Note that a beam element is used in this calculation to be simple.

This new method and conventional FEM method were applied into the medium-pressure pipeline networks in Koto-ku area of Tokyo which were divided into 3,000 elements, to compare their calculation volume. For conventional FEM by super-computer, it took 15 days. On the other hand, for NeEX with desk-top PC, it took only 2 minutes to complete the calculation. Then, it was proved that the calculation time in the new method is only 1/10,000 of the one of the conventional FEM.

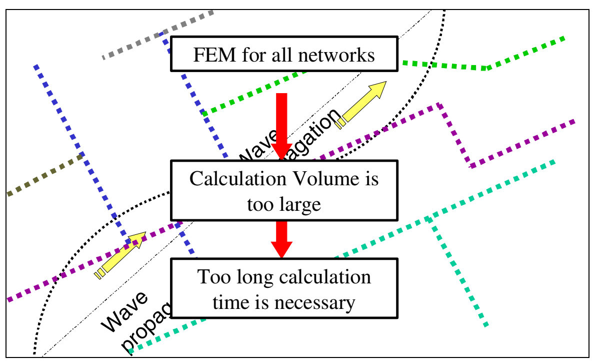

Fig.6: FEM for All Networks

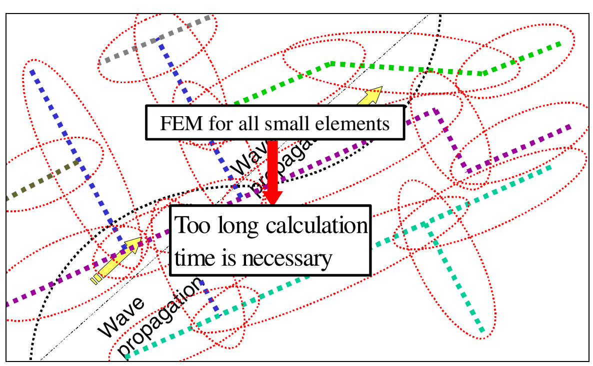

Fig.7: FEM for all networks which are divided into many small elements

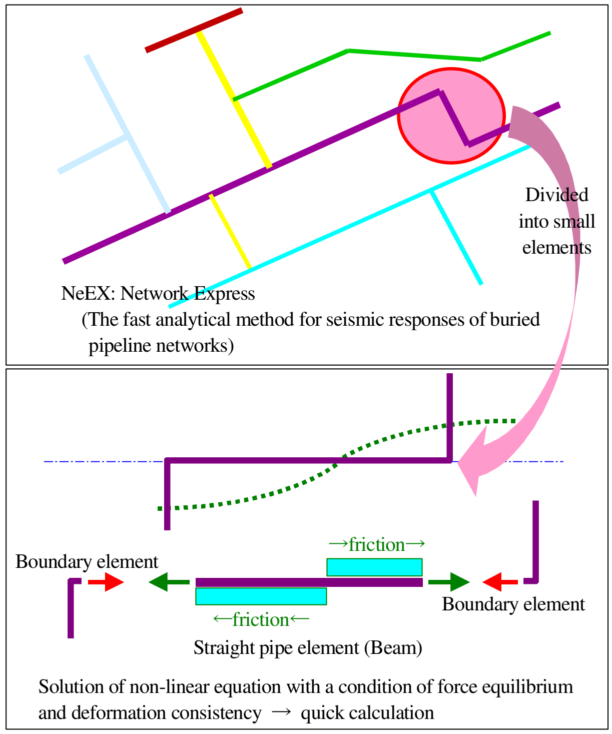

Fig.8: Development of NeEX

With regard to the accuracy of calculation, it was proved that the calculation result by the NeEX coincides with the one of FEM for axial force calcution.[4] For example, the result analyzed by NeEX is compared with the result of FEM, and a network like Fig.9 is summarized into Table2.

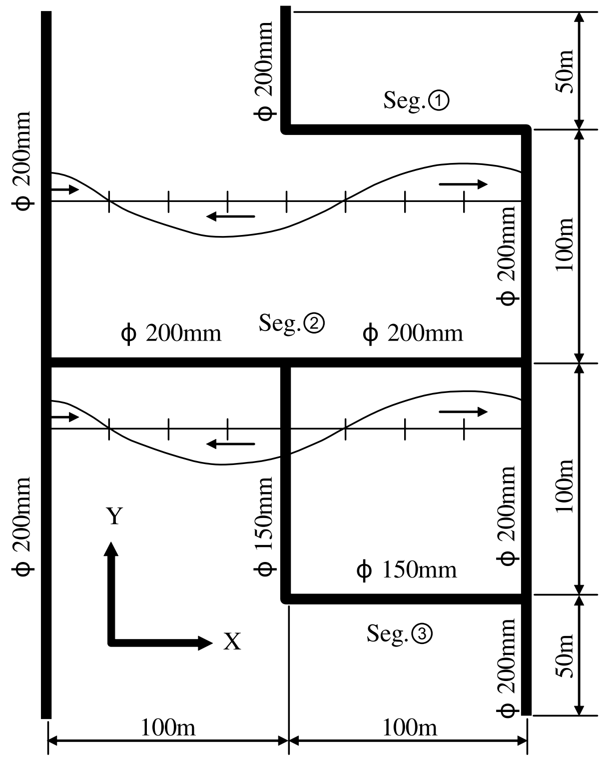

Fig.9: Example of a part of a buried pipeline network

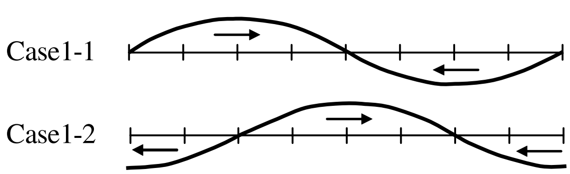

Table 2: Examples with 200m wave length

	Case 1-1			Case 1-2		
	δ B(cm)			δ B(cm)		
	Segment Model	FEM	Error (%)	Segment Model	FEM	Error (%)
①	-10.42	-10.55	1.2	-17.59	-17.60	0.1
②	10.41	10.52	1.0	-17.59	-17.60	0.1
③	2.57	2.49	3.2	8.21	8.75	6.1
⑤	2.57	2.49	3.2	-8.21	-8.74	6.1
⑥	-7.56	-7.94	4.8	-25.94	-25.74	1.8
⑦	5.99	5.60	7.0	-6.60	-6.96	5.2

In spite of having cut down the very big amount of calculation, the seismic capacity evaluation of the network of the buried pipeline which has spread in field by this analysis technique of calculation accuracy became as compared with FEM, it is as good as several %, and possible.

Detrmination of Critical SI Value

At first, the vast volume of Tokyo Gas's medium pressure network, with 6,000 km length in total, was to be divided into small pipe elements, utilizing pipe data base, valve data base and soil database in SUPREME. After dispersion work, the number of elements reached 230,000.

Secondly, for each dispersed element, the NeEX was applied to calculate the maximum axial force or the maximum strain according to the ground surface deformation (Uh) by shaking.

Uh can be obtained by the following equation[2].

Uh = SI × T / (1.18 × 2 π)   (Eq.3)

where Uh: Ground surface deformation (cm)
SI: Spectrum intensity (cm / sec)
T: Natural period of ground at the element (sec)

Here, Uh depends on SI.
Then, if the calculated maximum axial force or the maximum strain exceds the strength of material used for the element, the element is judged as “damaged”. Therefore the “critical” condition can be defined where the calculated values are equal to the strength of the element. Consequently the critical Uh, in other word, critical SI value, SIc, can be obtained, for each element, as shown in Fig.10.

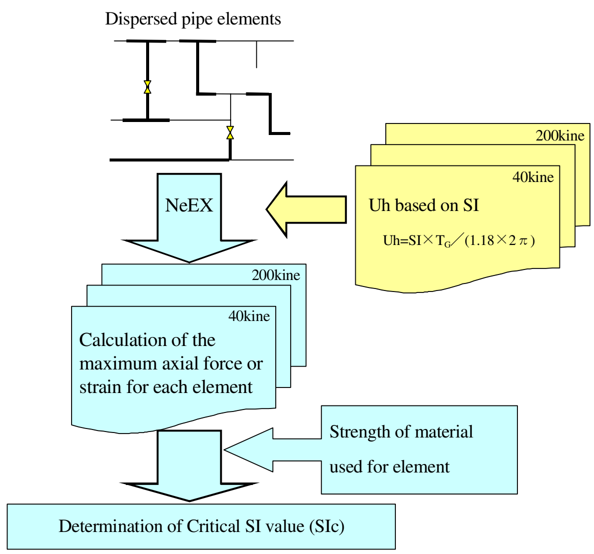

Fig.10: Determination of Critical SI Value

Although the evaluation to a shaking has been described so far, if the calculation method of the amount of foundation displacement of having taken into consideration the liquefaction, such as liquefaction intensity of the foundation, position relation between shore and a buried pipe, and type of shore, the foundation by liquefaction is permanent, the earthquake resistance over displacement can also be evaluated by the same method.

Seismic Resistance Evaluation Method

The seismic resistance evaluation for buried pipeline can be conducted easily to compare the design SI value on the surface ground (SIs) with the critical SI value (SIc) for each element.

If SIs   SIc, then the pipe element is judged to have poor seismic resistance and the replacement or reinforcement is to be planned.

If SIs   SIc, then the pipe element is judged to have sufficient seismic resistance.

This method has been already applied to Tokyo Gas’s medium pressure pipeline network. One of the results is shown in Fig.11. For example, there are 1,500 cast iron valves in Tokyo Gas and after this evaluation, only 10% of them was proved to be replaced or reinforced and the rest of them was judged to have sufficient seismic resistance. Tokyo Gas has already started to replace them and plans to finish the work by 2003. Thus, utilizing the new seismic resistance evaluation method, the over-investment can be avoided.

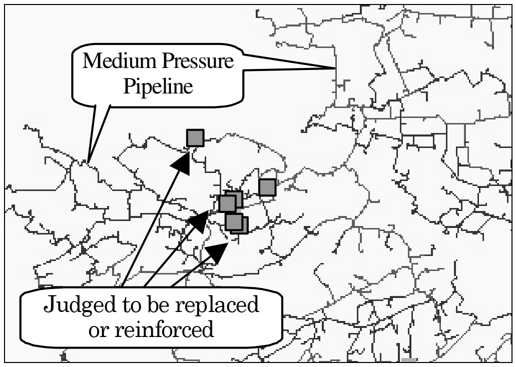

Fig.11: Seismic Resistance Evaluation

Utilization in SUPREME

Conventionally, the fragility curve based on the pipe damage experience in past earthquakes has been used for the real-time damage assessment. It seems to be practical for low pressure ctiy gas networks because there are ample damage cases in past earthquakes. However, for medium pressure or high pressure city gas networks, this method is not suitable because in the past earthquake, there was not much pipe damage case and the accuracy of the fragility curve cannot be assured.

Here, the new method to evaluate the seismic resistance of buried pipeline networks has been developed and the database of “critical SI value, SIc” for all 230,000 elements has been prepared. On the other hand, in SUPREME, the SI distribution (SIr) can be determined very precisely on GIS with 1.4 million 50m×50m maps in real-time just after earthquakes, utilizing 3,700 new SI sensors and site amplification database shown in Fig.12[5)]. Then, it is quite easy to conduct accurate damage assessment for medium pressure pipeline if comparison between SIc and SIr is conducted.

This method has been already installed in SUPREME and the damage assessment will be conducted as shown in Fig.13 and 14 when a big earthquake happens. The results of damage assessment will be big assistance for decision making of emergency response.

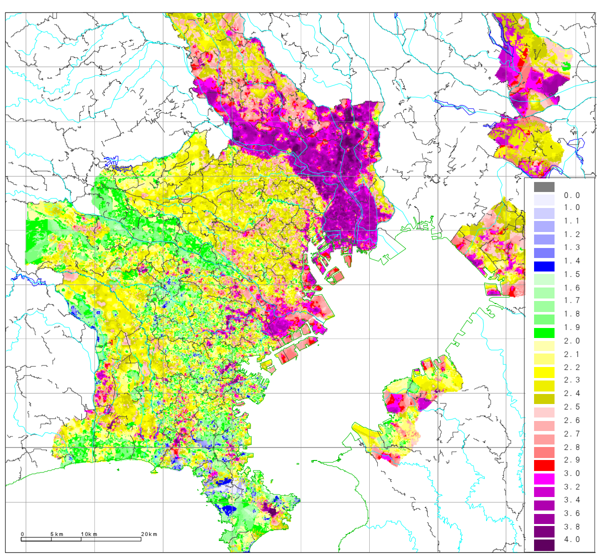

Fig.12: SI Amplification Database in SUPREME

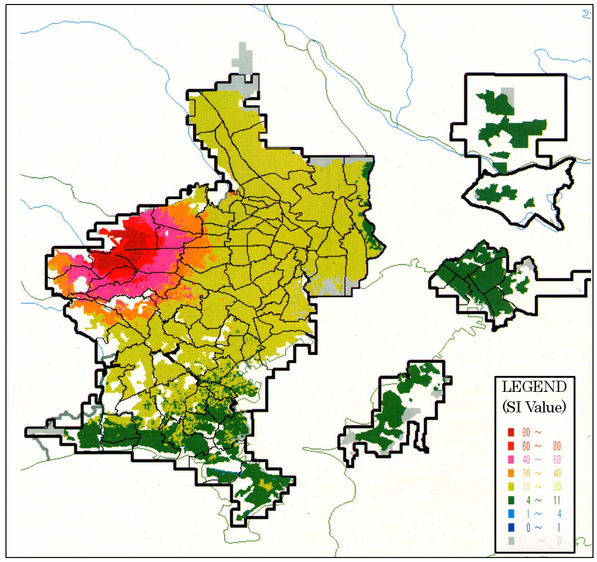

Fig.13: Real-time SI value distribution (SIr) under assumption of Tachikawa Earthquake

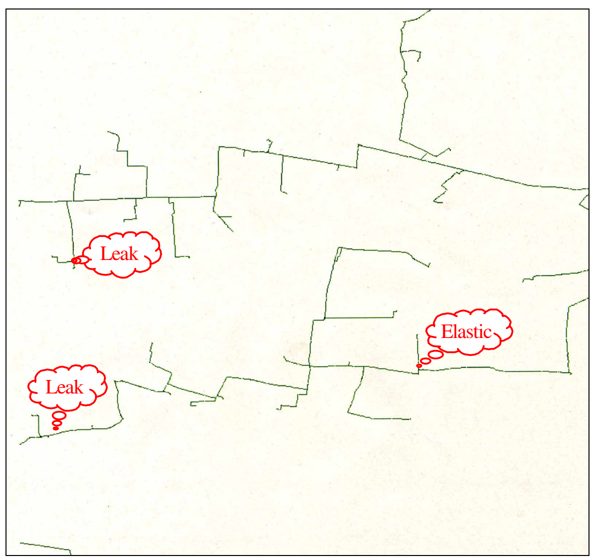

Fig.14: Results of damage assessment for medium pressure pipeline in SUPREME, under assumption of Tachikawa Earthquake

Conclusion

The new evaluation method for earthquake resistance of buried pipeline networks has been developed. Utilizing this method, the over-investment for the replacement of medium pressure pipes can be realized. The major achievements are described in what follows.

1) The seismic design external forces based on the "Seismic Design Guideline for High-Pressure Gas Pipeline" has been expressed as the "Design SI value on the surface ground (SIs)", utilizing a total of 60,000 bore-hole logging database in SUPREME.
2) The database of compression and tensile strength for all materials used in medium pressure gas pipeline has been prepared through lots of experiments.

3) The new and vast analytical evaluation method for seismic responses of buried pipeline networks, namely NeEX (Network Express), has been developed.
4) After dispersion of 6,000km length medium pressure pipeline networks, the NeEX was applied to calculate the “critical SI value (SIc)” “for all 230,000 elements, utilizing material strength database and soil database.
5) The simple and accurate seismic resistance evaluation for buried pipeline has been realized with comparison between SIs and SIc.
6) The accurate real-time damage assessment for medium pressure pipeline has been realized through comparison between the “Real-time SI value (SIr)” obtained in SUPREME monitoring system and SIc. This logic has been already installed in SUPREME and it will be a great assistance for decision making on emergency response.

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