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# REALTIME ESTIMATION OF CITY GAS PIPE NETWORK DAMAGE BY LATERAL FLOW OF LIQUEFIED GROUND BEHIND QUAY WALLS

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## SUMMARY

Estimating the degree of damage to city gas pipe networks is difficult because the lack of damage case data precludes the use of a statistical method of damage estimation like the one used for screwed-joint steel pipes. Seismic strengthening of gas pipes requires the identification of damage locations. This study aims to use the cause–effect relationship in which damage results when the amount of pipe foundation or load caused by ground motion or ground flow has exceeded a certain limit in order to estimate city gas pipe network damage. In this study, $P_L$ value (liquefaction risk index) distribution maps are constructed on the basis of the seismic forces assumed by the current seismic design guidelines, and pipe damage locations are extracted from the areas with a $P_L$ value of 5 or more and within a distance from a revetment of 100 m. This paper proposes a method for calculating the amount of earthquake-induced ground displacement at pipe node locations by constructing ground models based on boring data obtained at the nearest boreholes and using a simple ground flow formula.

## 1. INTRODUCTION

Estimating the degree of damage to high-strength city gas pipe networks is difficult because the lack of damage case data precludes the use of a statistical method of damage estimation like the one used for screwed-joint steel pipes [1]. For the seismic strengthening of gas pipes, the identification of the exact locations of damage is desired, but techniques depending on a vague indicator such as "the number of damage locations per unit length of pipe" do not meet that need. This study, therefore, aims to develop an analysis method for clearly expressing the cause–effect relationship in which damage results when the amount of pipe deformation or load caused by ground motion or ground flow has exceeded a certain limit, and to use the analysis method for estimating city gas pipe network damage. Such an analysis method makes it possible to calculate the allowable limits of damage-causing factors such as ground motion and

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ground flow for different pipe network elements. This paper deals with the development of a method for estimating city gas pipe network damage caused by liquefaction-induced ground flow behind revetments.

## 2. ANALYSIS FLOW

Since a city gas pipe network usually includes a vast length of pipes, it is necessary to narrow down the list of sites to be analyzed from various viewpoints. For this purpose, various digital data including $P_L$ value (a liquefaction risk index) distribution data, coast and river data and topographic and geotechnical data, along with field investigation results if necessary, are used. Figure 1 shows the procedure of this analysis method. $P_L$ value distribution data used for this purpose are those prepared from sufficiently strong seismic forces by referring to various guidelines.

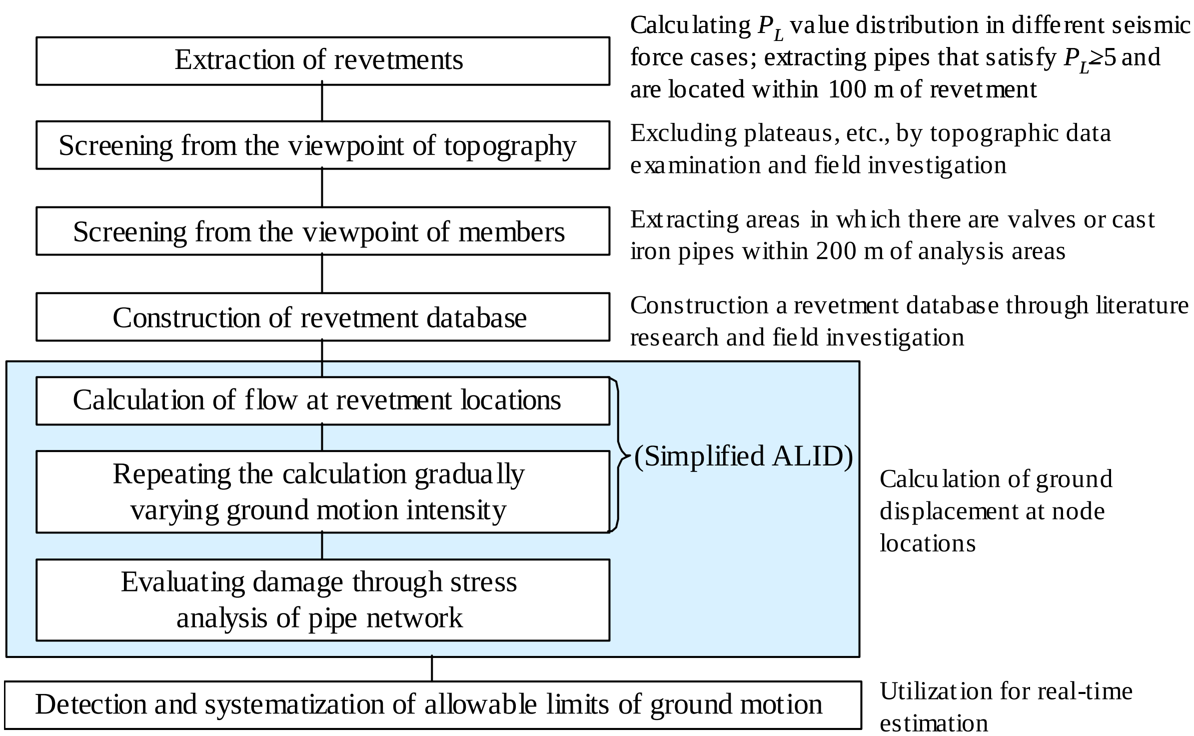


**Figure 1: Analysis procedure**

Stress analysis of a gas pipe network requires information on ground displacement at each node. Ground displacement can be calculated by using ALID, a two-dimensional FEM liquefaction-induced flow analysis program [2]. There is a simplified formula (hereafter referred to as the "Simplified ALID") derived by extracting important parameters from the ground parameters needed by ALID and performing regression analyses of the results of representative ground and revetment data [3]. In this study, ground displacement at different nodes in a city gas pipe network is calculated by using the Simplified ALID. The displacement values thus obtained are given to the pipe network to check, through stress analysis, whether or not they are within the allowable range.

By conducting stress analyses for all surface ground motions, allowable values of ground motion are extracted and integrated into a database. In the event of a real earthquake, damage risk can be evaluated quickly by comparing these allowable values with observed ground motion values.

## 3. PREPARATION OF $P_L$ VALUE DISTRIBUTION DATA

The real-time damage estimation system for low-pressure gas pipes reported in Reference 1 uses ground motions having a design seismic coefficient of 0.4 (marine earthquake) in preparing strong-earthquake liquefied layer thickness distribution data. It has been confirmed that if this seismic coefficient value is used as an input, the liquefaction resistance factor ($F_L$ value) for liquefiable soil at all depths (sandy soil with N-values ranging between 4 and 20 or so at depths of 20 m or less below ground surface) almost always becomes smaller than 1.0, so greater seismic coefficient values do not have significant impact on liquefied layer thickness.

The Seismic Design Guidelines for High Pressure Gas Pipelines against Liquefaction [4] (hereafter referred to as "SDG-L ") specify $P_L$=5 as the range for which ground flow analysis is to be conducted. Therefore, by collecting $P_L$ value distribution data, areas to be analyzed can be reduced considerably. Since, however, the $P_L$ value increases as the $F_L$ value of each layer decreases, the seismic forces used for low-pressure gas pipelines (for liquefied layer thickness) are not necessarily enough to be on the safe side in preparing $P_L$ value distribution data. The Seismic Design Guidelines for High Pressure Gas Pipelines [5] (hereafter referred to as "SDG") assume seismic forces that differ from those assumed by SDG-L (though liquefaction is beyond the scope of SDG). It is therefore necessary to take not only SDG-L but also SDG into consideration as guidelines related to gas pipelines. It was decided, therefore, to refer to these guidelines and conduct a study on buried gas pipelines, assuming the seismic forces shown in Table 1.

**Table 1: Assumed seismic forces**

| Case | Design standard | Seismic force |
|---|---|---|
| 1 | SDG-L [4] | Marine, $K_h$=0.4* |
| 2 | | Inland, $K_h$=0.8 |
| 3 | | Marine, $K_h$=0.3, 0.35, 0.4 (for different types of ground) |
| 4 | | Inland, $K_h$=0.8, 0.7, 0.6 (for different types of ground) |
| 5 | SDG [5] | Marine, level 2 |
| 6 | | Inland, level 2 |

* seismic force used in connection with low-pressure gas pipelines

In Cases 3 to 6 shown in Table 1, ground motions reflecting the natural period of the surface layer are given as inputs in accordance with applicable guidelines as shown in Table 2. Since, however, SDG [5] indicates response velocities for bedrock ground motions, the ground motions in Cases 5 and 6, in their original forms, cannot be used for the calculation described in SDG-L [4]. These ground motion values are multiplied by a single-mass-system-to-continuum conversion factor ($4/\pi$) to obtain maximum surface velocity values (cm/s). These values are then multiplied by another conversion factor (1.18) to obtain surface SI (spectral intensity) values (cm/s). From these values, seismic shear stress ratios are calculated by the method proposed by Yasuda et al. [6]. The lower numbers shown for Cases 5 and 6 in Table 2 are surface SI values (cm/s). Figure 2 shows the natural period distribution of the surface layer at boring sites. As an example, Figure 3 the distribution of $P_L$ values in Case 4.

**Table 2 Relationship between natural periods of surface layer and design ground motions used by different guidelines**

| Natural period of surface layer (s) | | | 0.1 | 0.2 | 0.6 0.7 |
|---|---|---|---|---|---|
| Type of ground | | | Class I | Class II | Class III |
| 3 | SDG-L [4] | Marine | 0.3 | 0.35 | 0.4 |
| 4 | (design seismic coefficient) | Inland | 0.8 | 0.7 | 0.6 |
| 5 | SDG [5] | Marine | 50 (cm/s) SI=75 (cm/s) | Logarithmic linear interpolation | 50 (cm/s) SI=75 (cm/s) |
| 6 | (maximum velocity) (cm/s) | Inland | 50 (cm/s) SI=75 (cm/s) | Logarithmic linear interpolation | 100 (cm/s) SI=150 (cm/s) |

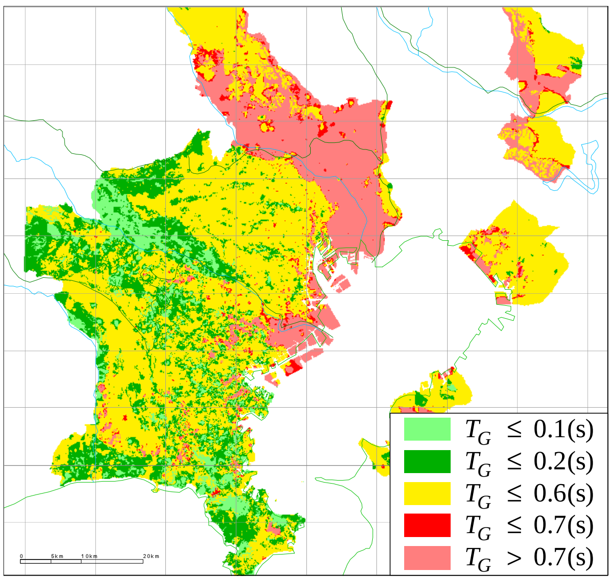


**Figure 2 Natural period of surface layer**

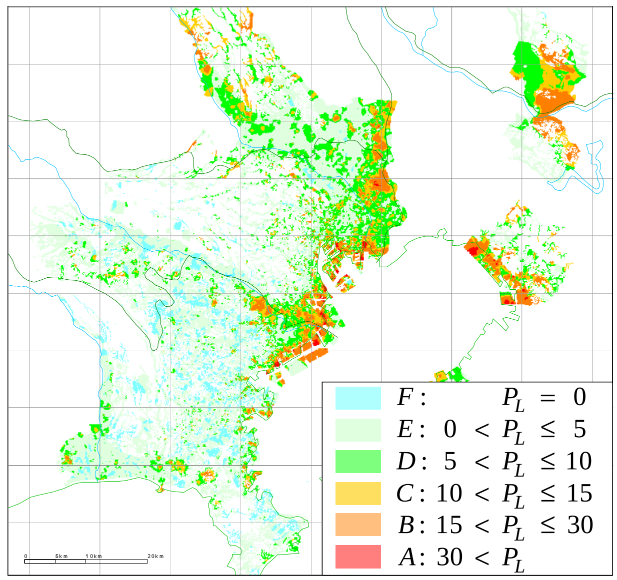


**Figure 3 $P_L$ value distribution of Case 4 (SDG-L, inland)**

## 4. FLOW CALCULATION BY SIMPLIFIED ALID

The Simplified ALID [3] has the following parameters:

$$D = f_1(L, L_{10}, D_{max}) \tag{1}$$
$$D_{max} = f_2(H_L, H_W, F_L, F_C) \tag{2}$$
$$L_{10} = f_3(H_L, H_W, F_L, F_C) \tag{3}$$

where $D$ is ground displacement (m) at a node; $L$, the distance from the revetment to the node; $D_{max}$, revetment displacement (m); $L_{10}$, influence range (the distance from the revetment to a point at which displacement reaches 10 cm); $H_L$, thickness of the liquefied layer (m); $H_W$, water depth (m); $F_L$, liquefaction resistance factor ($F_L$ value); $F_C$, fine grain content (%); and $f_1$, $f_2$ and $f_3$, functions for different types of revetment (sheet pile/gravity). $H_L$ is the total thickness of the layers that have been judged to be liquefied as a result of liquefaction evaluation [7] based on the $F_L$ method. $F_L$ and $F_C$ are representative values for layers that have been judged to be liquefied by the same method. Liquefaction evaluation requires the input of surface ground motion intensity. Consequently, the parameters $H_L$, $F_L$ and $F_C$ are dependent on surface ground motion intensity, and therefore $D$, too, is dependent on ground motion intensity. Tokyo Gas's real-time earthquake monitoring system, SUPREME [1], uses spectral intensity (SI) as a ground motion indicator. Since this makes it necessary to build a database of allowable SI values, SUPREME uses a SI-based liquefaction evaluation method [6].

## 5. DEVELOPMENT OF REVETMENT DATABASE

Calculation of ground displacement (m) at a node location by use of the Simplified ALID requires information such as water depth (m), the type of revetment and the location of the revetment nearest to the node. Calculation of the parameters $H_L$, $F_L$ and $F_C$ requires geotechnical data needed to use the $F_L$ method. The ground data here should be data on a site nearest to the revetment location instead of the node location.

In consideration of these factors, the ground-behind-revetment model was simplified as shown in Figure 4, and a revetment database was constructed. Since nearest revetment locations vary with pipe nodes even among revetments of the same type, a "pipe node–revetment link" database was constructed separately for the case shown in Figure 4. Simplified ALID calculation was performed for each pipe node–revetment link.

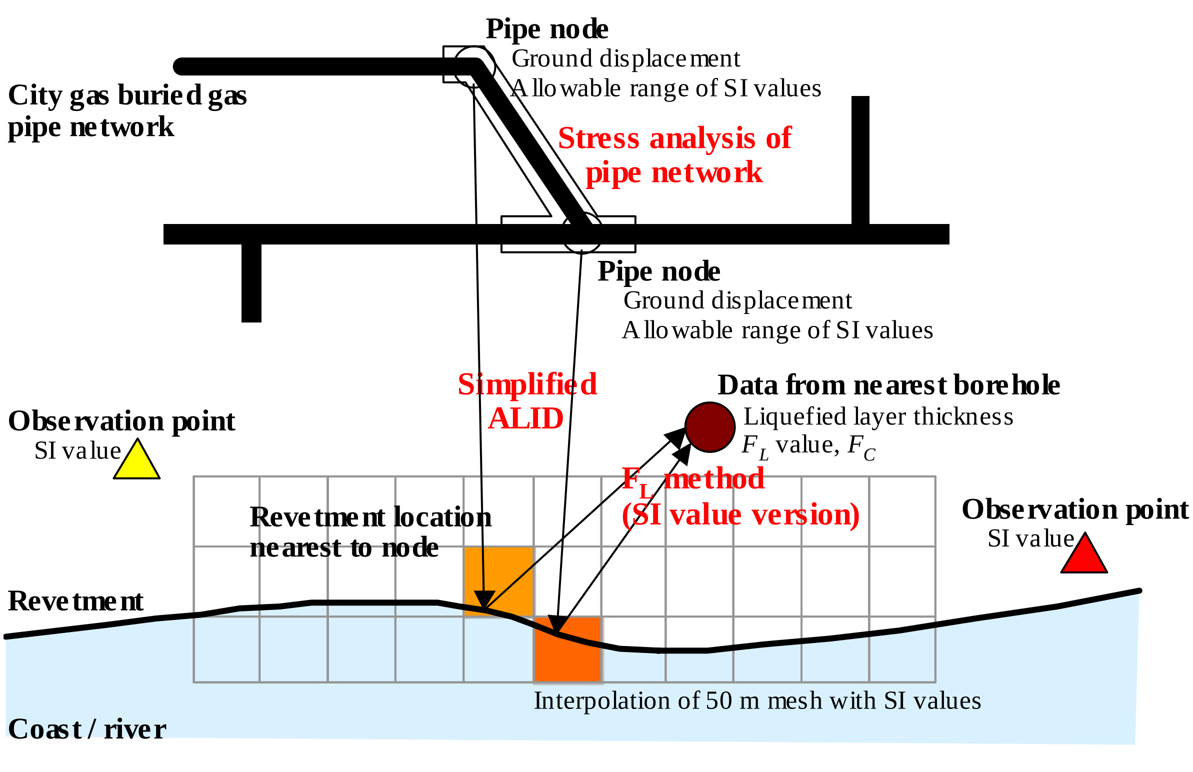


**Figure 4: Simplified model of ground behind revetment**

The revetment database contains only data concerning revetments related to the gas pipes identified as shown in Figure 1. In the category of river revetments, only revetments of 5 m or wider rivers were considered. To obtain river and coast information, shortest distances from digital gas pipe network data were computed using the "inland water area" data of Digital Map 2500 (spatial data framework). River information was also read off from paper-based residential maps for individual confirmation. For geotechnical data, data most relevant to each revetment were extracted from the 60,000-borehole boring database reported in Reference 1.

Figure 5 shows an example of gas pipe–revetment link data actually prepared as part of the revetment database. In Figure 5, circles represent boring sites, and the colors in the circles indicate $P_L$ values. The background colors indicate $P_L$ values interpolated into 50-meter mesh data. The green and red line segments show the linear alignments of gas pipelines, and the pink line segments represent gas pipe–revetment links.

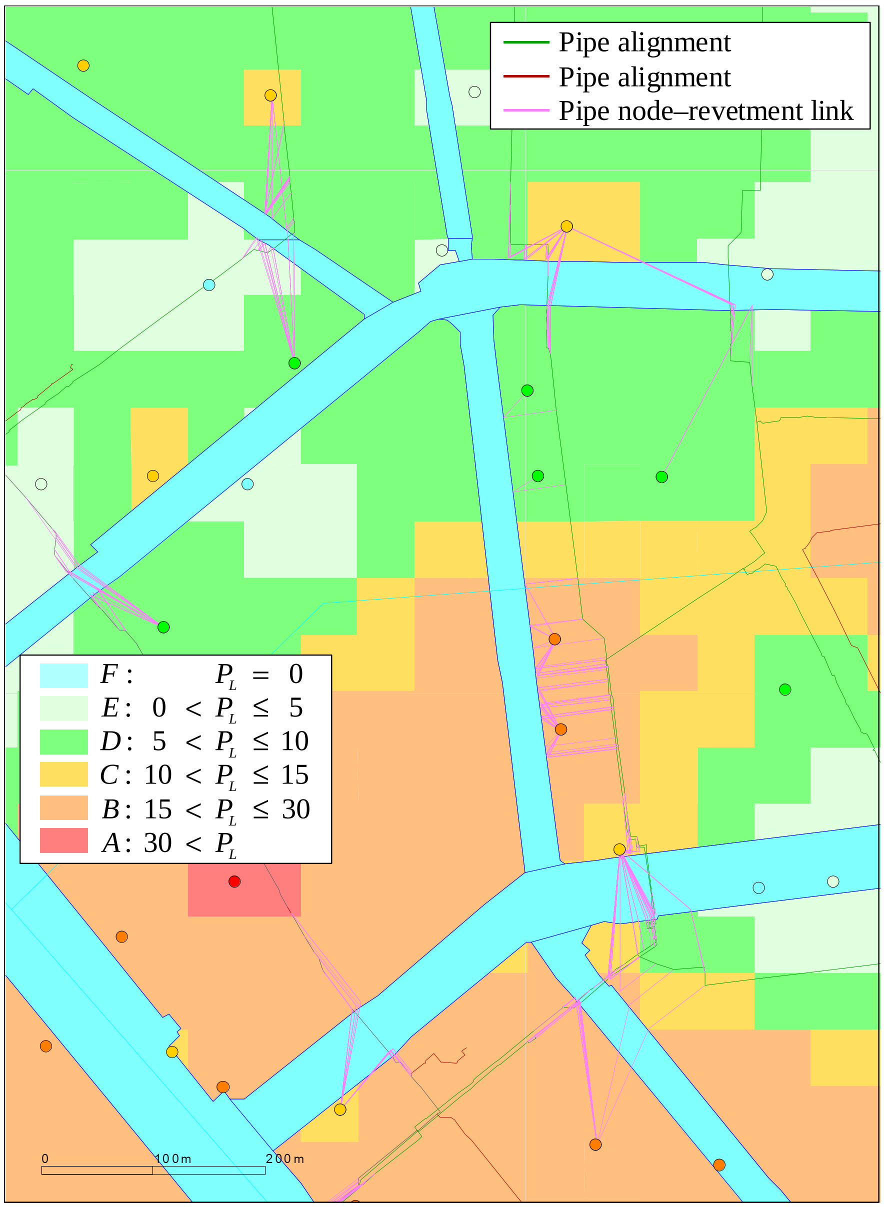


**Figure 5: Example of pipe node–revetment link display**

## 6. NEXT CHALLENGE

The natural period (s) of the surface layer used for the purposes of this study is a characteristic value $T_G$ (s) for ground calculated for determining the type of ground in SDG-L [4]. The natural period used in SDG [5], however, is calculated somewhat differently from $T_G$, and for strong earthquakes, a natural period calculated by reducing S-wave velocity to 70% is used. For combined use of SDG-L and SDG, therefore, it is necessary to discuss ways to achieve consistency.

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