EFFECTIVENESS OF THE DEFORMABILITY-EVALUATION FOR BURIED PIPELINES USING THE GROUND-BLOCK METHOD

Nobuaki NISHIO[1]

SUMMARY

Some big gas companies in Japan plan to develop a kind of "early warning and shut-off system" to minimize the number of suspended customers and to help early restoration of gas supply after an earthquake.
Those systems, however, will be effective only if the estimate of damage is sufficiently accurate. If it is not accurate enough, the optional shut-off will cause even greater secondary disaster.
The author has already proposed a method of estimating damage ratio for buried pipelines. This method is more reasonable than any other method in that this takes account of three fundamental factors in the quantitative manner, i.e., the deformability of a pipeline system, the ground conditions of the areas in which the pipeline systems are installed, and the intensity of earthquake ground motion.
The very basic idea of the proposed method had been applied for the "Recommended Practice for Earthquake-Resistant Design of Medium- and Low Pressure Gas Pipelines" published by the Japan Gas Association (JGA). In this Design Practice, the earthquake-resistance of a pipeline system is evaluated on the basis of the "deformability" of the pipeline system, which is evaluated by using the "ground-block model", and in reference with the ground conditions that are classified on the basis of the nonuniformity of topographical structure.
This paper discusses that the ground-block model is an almost rigorous expression of the nonuniform ground deformations. This also shows that the investigations of damage to gas pipelines, by JGA, during both the 1993 Kushiro-oki and the 1995 Hyogoken-nanbu earthquakes, proved clearly the effectiveness of the method used in the "Recommended Practice." This fact will also support the reliability of "deformability evaluation" based on the ground-block model.

INTRODUCTION

Most of big gas companies located in earthquake-prone areas take measures of dividing pipeline networks into isolated segments. This isolated-network system is expected to help minimizing the number of out-of-service customers by stopping gas-supply to pipeline-segments that sustained heavy damage to gas pipelines, while maintaining supply to the less sustained segments. This is also expected to help early restoration of gas supply after an earthquake.

Some gas companies intend to develop more improved systems that can be called "early (or real-time) warning and shut-off systems". These systems estimate the degree of pipeline damage for each pipeline-segments immediately after an earthquake, and automatically shut off supply to heavily damaged segments, thus preventing secondary disaster to be caused by gas leakage.

Those systems, however, will be effective only if the estimate of damage is sufficiently accurate. If it is not accurate enough, the optional shut-off will cause even greater secondary disaster.

[1] *Dr. Eng. (Ex-researcher at Tokyo Gas Company, Fundamental Technology Research Institute) E-mail nnishio@os.rim.or.jp*

Table 1 Required minimum values of Deformability Index for the combination of the pipeline classification and the ground conditions

unit: cm

Ground Condition / Pipeline classification	I	II	III
0.3～1.0 MPa lines	4.5	6.5	9.0
0.1～0.3 MPa lines	3.5	5.0	7.0
Low pressure Mains	2.5	3.5	5.0
Low pressure Services	3.5	5.0	5.0

The author has already proposed a method of estimating damage ratio for buried pipelines [Nishio 1992, Nishio 1994]. This method is more reasonable than any other method, because this takes account of three fundamental factors for pipeline-performance evaluation: they are the deformability of a pipeline system, the ground conditions of the areas in which the pipeline systems are installed, and the intensity of earthquake ground motion.

The very basic idea of the proposed method had been applied in the "Recommended Practice for Earthquake-Resistant Design of Medium- and Low Pressure Gas Pipelines" published by the Japan Gas Association (JGA)[JGA 1982]. In this Design Practice, the earthquake-resistance of a pipeline system is evaluated on the basis of the "deformability" of the pipeline system, which is evaluated by using the "ground-block model", and the ground conditions that are classified on the basis of the nonuniformity of topographical structure.

The idea of ground-block model is quite simple but realistic and effective. In this paper, the ground-block model is closely reexamined, and the effectiveness is demonstrated.

OUTLINE OF THE EARTHQUAKE-RESISTANCE EVALUATION FOR MEDIUM- AND LOW-PRESSURE GAS PIPELINES BY THE JGA PRACTICE

Classification of ground conditions

The minimum required value of the Deformability Index of a pipeline system is stipulated in accordance with the combination of the ground conditions and the importance of the given pipeline system.

The ground conditions are classified into the following three categories.

I. Stiff grounds with short natural periods that show small seismic displacements in general. Rocks dating back to the Triassic Era or earlier and the Diluvium layer are typical examples of category I ground conditions.

II. Soft grounds with long natural periods that show large seismic displacements in general. For example, soft alluvium layers more than 10 m thick.

III. Mixture of soil layers equivalent to Condition I and that equivalent to Condition II.

Required values of "Deformability Index" of pipeline systems

The required minimum values of Deformability Index for pipeline systems are stipulated as shown in Table 1, in accordance with the combination of the kind of pipeline and ground conditions.

This table shows that, for low-pressure mains, the Deformability Index of 5 cm is normally required for areas consisting of Condition III grounds. This also shows that the nonuniform ground (mixture of stiff and soft layers) is presumed to be in worse condition than the uniformly distributed soft layers, contrary to the general understanding that soft soils are more susceptible to earthquake damage than stiff soils.

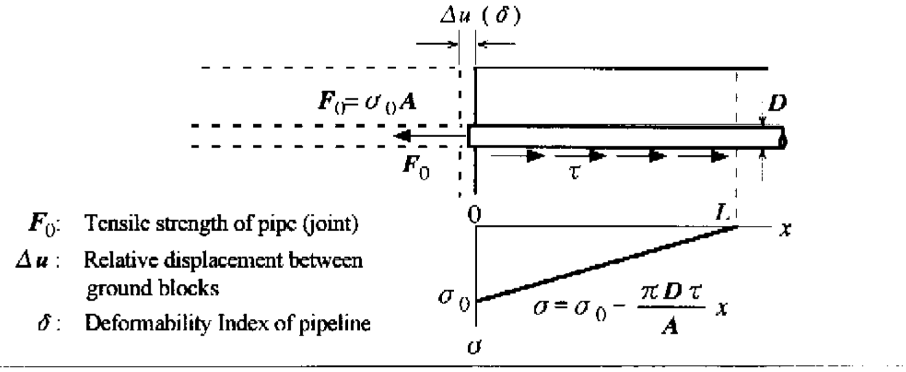


Figure 1 Ground-block model and the stress-distribution in a pipeline system

Definition of the Deformability Index based on the ground-block model

The axial deformation capability, δ, of a pipeline system is defined by the maximum relative displacements, Δu, between two ground blocks, under which leakage is caused to the pipeline spanning the two ground blocks (Figure 1). This value of δ is named the "Deformability Index."

In the ground-block model, slippage between the pipe and the surrounding soil is presumed. The following is an example of calculation of the Deformability Index of a thread-jointed steel pipeline, 50 mm in diameter, which has widely been used for low-pressure gas mains for a very long period, until recently. It is assumed that a thread jointed socket is located at the boundary between two ground blocks (x=0 in Figure 1), and the axial load on the pipeline has just reached the tensile strength of the thread joint, F_0. The stress distribution in the pipeline shows the linear relationship with respect to the abscissa x, as shown in Figure 1.

The dimensions of the pipe, 50 mm in diameter, are:
Outside diameter D=6.05 cm
Sectional area A=6.77 cm^2.

The standard value of soil restriction for a galvanized pipe having service branches is recommended by the JGA Practice, as
τ=20 kPa.

The average tensile strength of thread jointed socket is; F_0=115 kN, according to pull-out tests, and the stress in the pipeline corresponding to this F_0 value is; σ_0=160 MPa, approximately. This stress is lower than the yield stress of conventional mild steel that ranges between 250 and 300 MPa, approximately. This means that the strain in the pipeline is in the elastic range, and the elongation, δ, of the pipeline in the section of $-L \leqq x \leqq L$, is given by integrating the elastic strain as follows.

$$\delta = 2\int_0^L \left(\frac{\sigma}{E}\right) dx$$

$$= \frac{2}{E}\int_0^L \left(\sigma_0 L - \frac{\pi D \tau}{2A} x\right) dx$$

in which

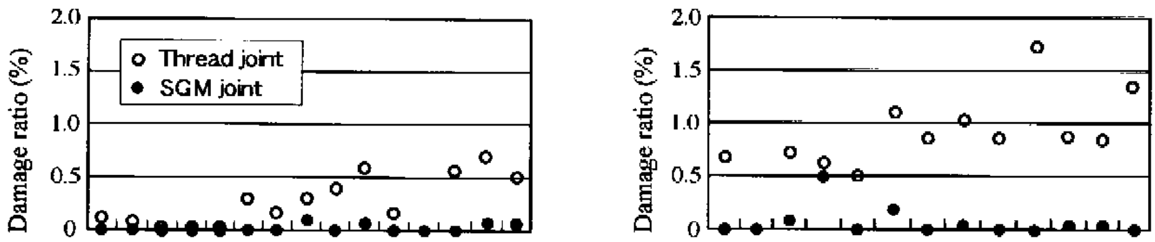
$$L = \frac{A\sigma_0}{\pi D \tau}$$

Therefore,

$$\delta = \frac{F_0^2}{\pi D \tau A E}$$

Table 2 Damage statistics for thread jointed steel pipelines, in the suspended areas, during the 1993 Kushiro-oki earthquake (classified by the topographical types)

Topographical type	Number of damage	Damage ratio (Number of damage/km)	Corresponding type of ground conditions by JGA Practice
Low land	0	0	II
Terrace	17	0.43	I
Mixed	35	1.47	III



a) Ground conditions I and II   b) Ground conditions III

Figure 2 Statistics of damage to low-pressure steel mains classified by the ground conditions (for the Kobe-No.4 pipeline-network segment, during the 1995 Hyogoken-nanbu earthquake: each division on the abscissa represents a subdivided network section)

Substituting the values for pipe dimensions and strength, described above, and the Young's modulus of E=2.05× 105 MPa, the Deformability Index of this pipeline system is given as
δ=2.7 cm .

This value indicates that the thread-jointed steel pipeline is not earthquake-resistant except for the use in the areas consisting of very stable soils, or the areas classified as Condition I .

VERIFICATION OF EFFECTIVENESS OF THE JGA-PRACTICE MODEL BY THE DATA OBTAINED DURING THE ACTUAL EARTHQUAKES

Analysis of damage to gas pipelines during the 1993 Kushiro-oki earthquake

The Japan Gas Association conducted a study on the relationship between the soil conditions and the damage ratios for the gas pipelines in the suspended areas during the 1993 Kushiro-oki earthquake [JGA 1994]. Table 2 shows the damage ratios of thread-jointed steel pipelines classified in accordance with the topography (damage was mostly sustained by the thread-jointed pipelines). Topographical types on the left column correspond to the ground conditions, classified by the JGA Practice, as shown on the right column.

The table clearly shows that damage ratio is the greatest in the Condition-III areas thus proving the JGA Practice to be reasonable.

Analysis of damage to gas pipelines during the 1995 Hyogoken-nanbu earthquake

A similar study was also made by the JGA on the damage to gas pipelines during the 1995 Hyogoken-nanbu earthquake [JGA 1997].

The ground conditions for network sections in one of the low-pressure network segments were classified according to the JGA Practice, and the damage ratio for each section was calculated. Figure 2 shows the result of

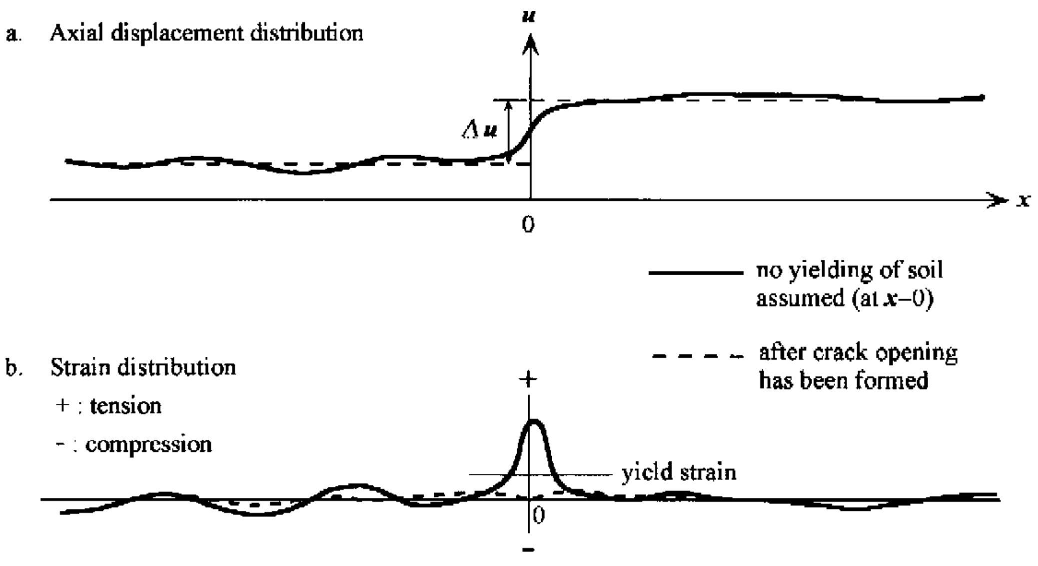


Figure 3 Schematic nonuniform ground displacement and accompanying strain distribution

the study.

The fact is clearly observed that Condition-Ⅲ areas, which represent great topographical nonuniformity, sustained the heaviest damage to thread-jointed pipelines, as in the case for the Kushiro-oki earthquake.

On the other hand, the damage ratios of SGM-joint pipelines, which use a kind of mechanical joint developed as the replacement for the thread joint and having Deformability-Index value of greater than 5 cm, are very small even in the Condition-Ⅲ areas.

The above facts prove the stipulation by the JGA-Practice to be correct that low-pressure pipelines must have the Deformability Index value greater than 5 cm in the areas of worst condition. This is likely to support the deformability evaluation using the ground-block model to be also reasonable.

PHYSICAL BASIS FOR THE GROUND-BLOCK MODEL

Nonuniform ground displacements

The technical standard of earthquake-resistant design of petroleum pipelines, which forms a part of the Petroleum Pipeline Industry Law of Japan, employs the travelling wave model as the forced displacement against pipelines. The strain associated with a travelling wave, however, should necessarily be the elastic strain that cannot cause failure to pipelines (a "plastic wave" cannot travel).

On the other hand, nonuniform surface soil layers can sustain sufficiently great strain (in the horizontal direction) to cause failure to pipelines, in response to S-waves that are incident vertically from the bottom of the surface layer.

An extremely nonuniform ground displacement, and the subsequent deformation in a pipeline can be described as follows:

A nonuniform distribution of displacements in the ground surface in the horizontal direction can schematically be expressed as shown by the solid line in Figure 3a. The strain distribution associated with the above displacement distribution can be expressed by differentiating the displacement u with respect to the abscissa x, as shown by the solid line in Figure 3b.

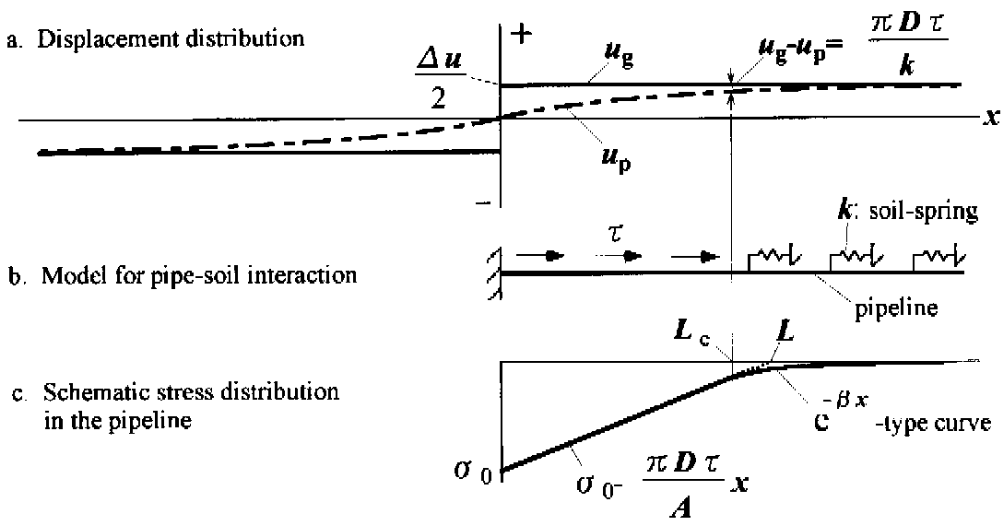


Figure 4 Pipeline response to crack-opening-type ground displacement

However, because the tensile yield stress of soils is extremely small, the soil easily fails and a crack opening is formed at the location where a great strain has first been produced (x=0 in Figure 3). As a result, the strain distribution is rearranged so as to be almost zero except for the location of crack (a crack opening implies infinitely large strain). The rearranged strain distribution is expressed as shown by the broken line in Figure 3b, and the corresponding displacement distribution is expressed as shown by two broken lines in Figure 3a which are almost straight lines, and the magnitude of crack opening is expressed as Δu.

Thus the same ground displacements as the ground-block model can actually be produced if the degree of nonuniformity of ground displacements is sufficiently large.

Restrictive force of soil against a pipeline

The fact is well known that slippage between soil and pipe occurs under quite small relative axial displacement. A certain calculation shows that slippage occurs under a relative displacement as small as 1 mm or even smaller, if the pipe diameter is as small as 300 mm [Nishio 1983].

On the other hand, the magnitude of crack opening in the ground, Δu, during the actual earthquakes can be on the order of centimeter or greater.

The pipeline-soil interaction for the ground-block model with such a great crack opening can be expressed as shown in Figure 4. It is assumed that the location, $x=L_c$, is the point where the magnitude of relative displacement between pipe and soil, i.e., u_g-u_p, reaches the critical value for slippage. Then the soil restriction takes a constant value of τ in the region, $0 \leqq x < L_c$, while the model of "a beam on an elastic foundation" applies for the region, $L_c \leqq x$.

The stress distribution in the pipeline for the above interaction-model can schematically be expressed as shown in Figure 4b.

The location L in the figure is the intersection of the extension of stress distribution for the slipped region and the x-coordinate.

Because the magnitude of relative displacement between pipe and soil at the onset of slippage is very small, the abscissas, L_c and L, are very close. Therefore, the region, $L_c \leqq x$, can be neglected, and the ground-block model, shown in Figure 1, gives an almost rigorous model of pipeline-ground interaction.

CONCLUSION

Analyses of damage statistics obtained during the 1993 Kushiro-oki earthquake and the 1995 Hyogoken-nanbu earthquake proved the following two facts:

1. The topographical nonuniformity bears extremely close correlation with the damage ratio of buried pipelines.
2. The evaluation of the "deformability" of pipelines by using the "ground-block model" is quite effective.

The above two facts have already been taken into account, by the present author, in editing the Recommended Practice of JGA for Earthquake-Resistant Design of Medium- and Low-Pressure Gas Pipelines.

The fact that the ground block model is a reasonable as well as practical expression of the pipeline-soil interaction under nonuniform ground displacements was further demonstrated.

The above results will support the reliability of the Damage Ratio Prediction Method, proposed by the author [Nishio 1992, Nishio 1994], which is based on the same idea and the model as are employed in the JGA Practice for Earthquake Resistant Design, in the more improved and quantitative manner.

REFERENCES

Japan Gas Association, 1982, "Recommended Practice for Earthquake-Resistant Design of Medium- and Low Pressure Gas Pipelines"

Japan Gas Association, 1994, Kushiro-oki Jishin, "Hokkaidou-nansei-oki Jishin to Toshi-Gasu (in Japanese, 1993 Kushiro-oki earthquake, 1983 Hokkaidou-nansei-oki Earthquake and Gas Facilities)"

Japan Gas Association, 1997, "Hyogoken-nanbu Jisin to Toshi-Gasu (1995 Hyogoken-nanbu Earthquake and Gas facilities)"

Nishio, N., 1983, "Characteristics of Deformation in a Buried Pipeline Under Sinusoidal Ground Motion", *Natural Disaster Science*, Vol. 5, No. 1, pp.53-68

Nishio, N., 1992, "Seismic Damage Ratio Prediction for Buried Pipelines Considering Nonuniform Ground Displacement", *Structural Eng./Earthquake Eng.*, JSCE, Vol.9, No.2, 151s-162s

Nishio, N., 1994, "Damage Ratio Prediction for Buried Pipelines Based on the Deformability of Pipelines and the Nonuniformity of the Ground", *Journal of Pressure Vessel Technology*, ASME, Vol. 116, pp.459-466