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SEISMIC DAMAGE RATIO PREDICTION FOR BURIED PIPELINES CONSIDERING NONUNIFORM GROUND DISPLACEMENT

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A new method is proposed to predict the possible damage ratio of buried pipelines during earthquakes. The method takes into account three fundamental factors ; namely, the deformability of pipeline system, the nonuniform ground conditions and the intensity of earthquake ground motion. The proposed method is then applied to damage statistics on gas pipelines obtained during three earthquakes. The result shows that the proposed method is sufficiently accurate as well as practical. Moreover, it is shown that the proposed method can take into account the liquefied grounds. Finally, applications of the proposed method for the evaluation of the earthquake resistance of pipeline systems are demonstrated on the basis of the above-obtained results.
Keywords : *earthquake, ground displacements, buried pipeline, damage ratio*

1. INTRODUCTION

It is essential to evaluate the degree of vulnerability of existing pipelines to estabish effective earthquake countermeasures. This is particularly necessary for utility pipelines, which form vast networks throughout wide areas encompassing various kinds of grounds.

The effects of a few typical types of ground displacements, such as fault movements and lateral spreadings, on the vulnerability of pipelines have been studied by a number of researchers ; however, a method to evaluate the effects of ground conditions in general has not yet been proposed except for a kind of statistical analyses of the correlation between ground conditions and the damage susceptibility of certain kinds of pipelines.

It is the intent of this paper to propose a method for predicting the damage ratio of pipelines using a definite model of ground-pipeline interaction, and making the most of the knowledge obtained from damage statistics and observation of actual pipelines during earthquakes.

Damage statistics obtained during past earthquakes indicate the following :

1. Damage is concentrated to areas showing complicated (or irregular) ground conditions ; nonunifrom ground displacements due to the irregularity is considered to be the cause of large strains in the ground.
2. Vulnerability largely depends on the kind of pipeline system. It is obvious that the less flexible the pipeline (with respect to either pipe joints or pipeline materials), the more vulnerable it is.
3. As a matter of course, vulnerability also largely depends on the intensity of the seismic ground motion, which is usually represented by the maximum acceleration.

The proposed model will take into account the above three fundamental factors in quantitative and definite forms. The model will be simple and practical, while expressing the essence of seisimic ground motions and pipeline behavior.

An exapmle of the classification of ground conditions on the basis of the degree of nonuniformity of the ground will be presented. Examples of the evaluation of the vulnerability (or earthquake resistance) of existing pipeline systems will also be presented, using the above-obtained results, thus demonstrating the usefulness, as well as the rationality, of the proposed method of damage ratio prediction.

2. PRECEDING STUDIES ON FACTORS CONTRIBUTING TO PIPELINE DAMAGE

There are very few studies which are aimed at establishing a method for quantitatively predicting pipeline damge susceptibility, while clarifying the factors that affect the damage to buried pipelines. This is considered to be because there were few earthquakes during which damage statistics precise enough to analyze important factors could be obtained.

Among such studies, the following three works on the analysis of damage to water pipelines in Tokyo during the 1923 Kanto Earthquake are the most informative ones.

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(1) Characteristic feature of the local distribution of pipeline damage

Okamoto[1] pointed out that there was a remarkable difference in the local distribution between damage to wooden buildings and damage to water pipelines. Although both structures were more susceptible to damage in the areas with soft subsurface layers than in the areas consisting of stiff ground, the damage to the wooden buildings was concentrated in the Sumida basin and areas eastward of the Sumida River where uniform and soft alluvial deposits tend to develop. In contrast, damage to pipelines was concentrated in the western part of the Sumida basin where the ground changes from alluvium to diluvium, forming intricate geological conditions. Okamoto describes this fact by the following sentenses : "This naturally leads to supposition that ground motion was uneven for the various locations in the latter case. This is thought to have been the reason for the great damage to buried pipelines."

His observation, though it may be qualitative rather than quantitative, is considered to point out the true cause of pipeline damage in relation to dynamic ground motion.

(2) Study by Kubo et al.

Kubo et al.[2] proposed the classification of ground conditions in a quantitative relation to the damage ratio of cast-iron pipeline for water distribution during the Kanto Earthquake.

They divided the Tokyo City area into square meshes measuring 1km × 1km. The natural frequencies of the ground at the four corners of each mesh and the ratio of ground types constituting the mesh were used to quantitatively characterize the ground condtions of each mesh. The relationship between thus defined indices, based on natural frequencies and ground types, and the damage ratio of the pipelines in each mesh was investigated.

The results showed that the magnitude of deviation of the indices in a mesh was closely correlated to the value of the damage ratio. It was also found that the contribution of the average stiffness of the ground in the mesh to the damage ratio was the greatest when the ground was neither too soft nor too stiff.

These facts can be regarded as a different expression of the same facts that had been pointed out by Okamoto[1].

In the same study, Kubo et al.[2] established a relationship between the damage ratio and the maximum ground acceleration on the basis of the local distribution of damage to cast-iron water distribution pipelines in the suburban areas of Los Angeles during the 1971 San Fernando Earthquake. They showed that the obtained relationship matched well with the relationships observed during the other earthquakes. This relationship suggests the existence of a kind of threshold value of acceleration, about 250 cm/s^2 in this case, as cited in **Fig.4** in this paper.

(3) Study by Ichihara and Yamaguchi

Ichihara and Yamaguchi[3] quantitatively analyzed factors contributing to damage to water pipelines during the Kanto Earthquake using the first kind of quantification theory.

The most significant factor contributing to the high damage ratio was shown to be seismic intensity. In particular, the effect of the seismic intensity was shown to become significant when it exceeded an acceleration value of about 220cm/s^2. This result corroborate the results of Kubo et al. shown above.

Contribution of geological conditions was also shown to be very significant.

On the whole, the results of the study are likely to express almost the same facts as pointed out by Okamoto and the results of the analysis by Kubo et al., although the words used are different.

The studies of both Kubo et al. and Ichihara et al. are intended to enable a quantitative prediction of the damage ratio of pipelines on the basis of a quantification of the ground conditions and the effect of seismic intensity.

However, the application of these studies are limited to the same kinds of pipelines as those studied by them, namely, cast-iron pipelines of the early 20th century.

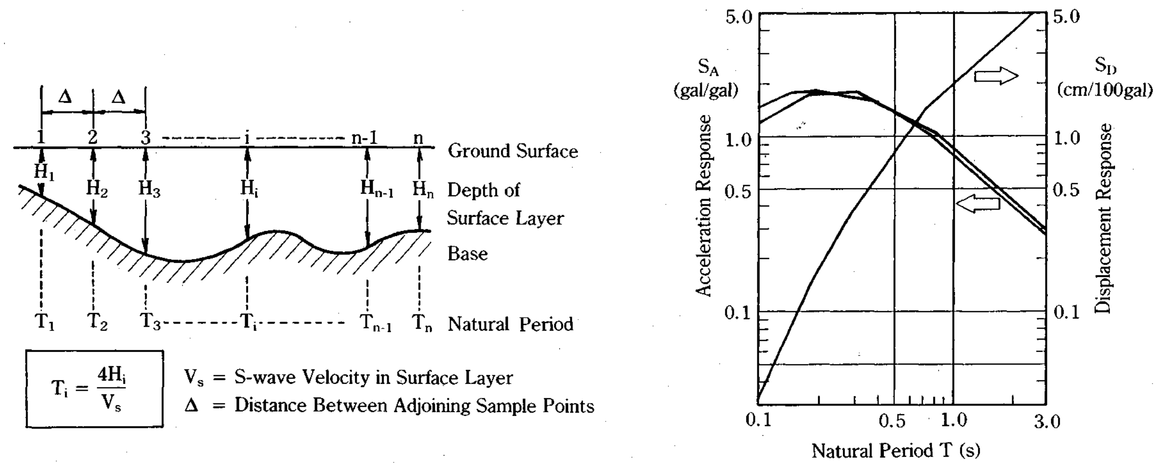
3. STRAIN IN BURIED PIPELINES BASED ON EARTHQUAKE OBSERVATIONS

The present author and his colleagues[4)~7)] have carried out earthquake observations on buried pipelines at five locations. They[8] have also carried out model experiments using dynamically similar models of surface layers, one of which caused heavy damage in thread-jointed steel pipelines for gas distribution during the 1978 Miyagiken-oki Earthquake.

Based on the above earthquake observations and model expeiments, the author[9,10] has shown a close relationship between the nonuniformity of the ground and the seismic strain in the pipelines. He introduced the "Nonuniformity Index" to quantitatively express the degree of nonuniformity in the ground.

(1) Nonuniformity Index, *NI*, based on the response characteristics of ground

The existing subsurface ground is necessarily "irregular" more or less. This irregularity in the



a. Determination of Natural Periods for Sample Points

b. Example of Average Response Spectra for Earthquake Records Taken on Stiff Ground (on Stiff Alluvium and Diluvium: After Kuribayashi et al.[11])
Note: gal=cm/s^2

Fig.1 Schematic Illustration of the Surface Soil Layer, and Method of Determining Expected Displacement Using the Average Response Spectrum

ground is represented by either the nonuniformity of the geological stratification or the variation in the depth of the soft subsurface layer. **Fig.1a** provides a schematic example of irregular ground.

This type of subsurface layer can be approximately expressed by a row of 1-degree-of-freedom vibrating systems with natural frequencies, T_i ($i=1 \sim n$), which are determined in the manner as shown in **Fig.1a**, neglecting the mutual effects between neighboring vibrating systems. As a result, the desplacement, S_{Di}, in the i-th vibrating system, which is expected to be produced by a unit intensity of earthquake motion, can be predicted by referring to the proper average response spectrum. The variation of the value of S_{Di} will be greater for a ground showing a greater degree of nonuniformity.

The formula of standard deviation of random variables can be one of the most convenient measures of expressing the degree of nonuniformity, although the quantity S_{Di} may not necessarily take random values. Accordingly,the following formula of standard deviation has been proposed to express the degree of nonuniformity of a ground, and has been named the "Nonuniformity Index" or *NI*.

$$NI=\frac{1}{n}\sqrt{n\sum_{i=1}^{n} S_{Di}{}^2-\left(\sum_{i=1}^{n} S_{Di}\right)^2}$$

The base of the surface layer should naturally be stiffer than the surface layer. Therefore, the average response spectrum to be used should be based on the earthquake records taken on stiff grounds. **Fig.1b** illustrates an expamle of the average displacement response spectrum. The average acceleration response spectra in **Fig.1b** are those proposed by Kuribayashi et al.[11] on the basis of records taken on diluviums and stiff alluviums. The displacement response spectrum S_D has been calculated on the basis of the average of the two acceleration spectra, S_A, using the equation $S_D=(T/2\pi)^2 \cdot S_A$ (note : in this case, the value of 100 cm/s^2 is taken as the unit acceleration for the displacement response).

(2) Relationship between the *NI* and strains in the pipelines

The values of the *NI* of the ground for earthquake observations and model experiments (Rrfs. 4, 5, 6, 7, 8) were calculated by referring to the displacement spectrum shown in **Fig.1b**, and were compared with the maximum axial strains in the pipelines observed. The results are shown in **Fig.2** where the strains are normalized with respect to the average maximum acceleration at each observation site or ground used in the mod el experiments.

It should be noted that the axial strains were five to ten times as great as the bending strains in every case. This is likely to correspond to the general understanding that axial forces are the dominant cause of pipeline failure during earthquakes.

The obtained relationship between the *NI* and the strain is almost linear. The exponent for the *NI* in the regression equation is 0.88 which is very

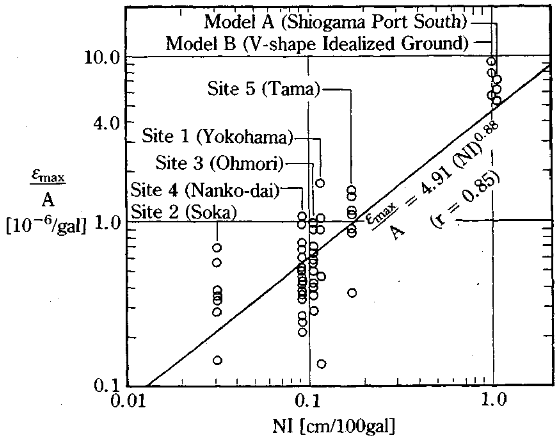


Fig.2 Relationship Between the NI and Maximum Strain in a Ground (Nishio[13])

close to 1, and the coefficient of correlation is as high as 0.85, which indicates a close correlation between the two variables,namely, the degree of nonuniformity of the ground and the strains produced in the pipelines.

4. METHOD OF DAMAGE RATIO PREDICTION —A PROPOSAL

The definition of *NI* is based on the fact that the magnitude of seismic displacements in the ground varies from one location to another depending on the geological conditions of a particular site.

This naturally means that the strains in the ground also vary from one location to another, thus forming a distribution with a certain magnitude of standard deviation. This standard deviation should be related directly to the value of the *NI*. Therefore, if the limit value of strain in the groud, up to which a certain kind of pipeline can survive without leakage or failure, is known, we can predict the probability of damage on the basis of the probability that the strain in the ground takes a greater value than the limit strain for the pipeline.

However, it is almost impossible to investigate the geological conditions of each site of pipeline construction precisely enough to obtain the value of the *NI*. The main reason is one of economy, since the cost of ground investigations is comparable to, or even higher than the cost of construction of distribution pipelines for utilities such as water and gas pipes which have small diameters (therefore, the cost is low) and form vast networks all over wide distribution areas (therefore, the quantity is enormous).

Therefore the author[12)-14)] has proposd a method of damage ratio prediction for buried pipelines, in which the probable degree of nonuniformity or the

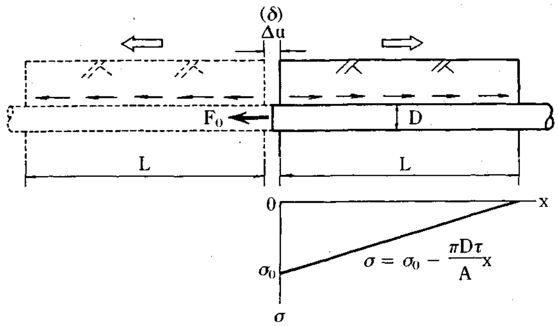


Fig.3 Ground-Block Model, and an Example of Stress Distribution in a Pipeline due to the Relative Displacement Δu Between Two Ground Blocks

value of standard deviation of seismic ground displacement, is estimated on the basis of damage statistics on pipelines obtained during past earthquakes.

In this method a ground-block model is used to make it simple and practical to evaluate the limit ground strain, or the allowable limit of deformation in pipelines. This ground-block model also simplifies the total model of damage ratio prediction, as will be described below.

(1) Definition of the "Deformability Index", δ

Fig.3 shows an example of a pipeline running across two ground blocks giving a relative desplacement of Δu. The pipeline is assumned to be continuous without having discontinuous pipe-joints except at the location of $x=0$.

This state of ground blocks is considered to represent approximately the state of the ground under a strain, the average magnitude of which is given as

$$\bar{\varepsilon}=\frac{\Delta u}{L},$$

provided that the size of the ground block, L, is given.

If the strain in the ground, or the relative displacement Δu, is great, slippage occurs between the ground and the pipe surface. Then the shear strength, or friction, τ, of the soil at the pipe surface can be taken into account as the cause of soil restriction, neglecting the effect of elastic deformation in the soil. The reason for this is given as follows :

The magnitude of relative displacement u_s at the elastic limit of soil restriction is given, assuming the soil to be an elastic-perfect plastic body, by the equation

$$ku_s=\pi D\tau$$

where k is the elastic coefficient, and D is the diameter of the pipe. The value of k is between $1G_s$ and $3G_s$ as Hmadi and O'Rourke[15)] have shown, where G_s is shear modulus of the soil. The value of G_s is on the order of 10 MPa at minimum, while the shear strength τ of common sandy backfill-soils is on the order of 20kPa at maximum. Therefore, for pipes smaller than several tens of centimeters in diameter, the magnitude of elastic relative displacement u_s is on the order of 1mm at most. On the other hand, the magnitude of Δu in question should be on the order of 1cm at the very least, so that damage could be caused to the pipeline. Therefore, **Fig.3** will give an almost exact model of ground-pipeline interaction with respect to the axial forces.

In such a case, as shown in **Fig.3**, the stress in the pipeline is given as

$$\sigma=\sigma_0-\frac{\pi D\tau}{A}x \quad\cdots\cdots(1)$$

where A is a cross sectional area of the pipe.

If the axial force acting on the joint at the center, or $x=0$, reaches the limit value F_0 under which the joint fails, then the stress σ_0 is expressed as

$$\sigma_0=\frac{F_0}{A}$$

Assuming that this stress does not exceed the yield stress of the pipe, and that there is no displacement or elongation in the joint, the total amount of elongation in the pipeline is given by integrating the strain due to the stress σ, which is given by Eq. (1), as follows :

$$\delta=\frac{2}{A}\int_0^L(F_0-\pi D\tau x)\,dx$$

$$=\frac{F_0^2}{\pi D\tau AE} \quad\cdots\cdots(2)$$

in which E is the Young's modulus of the pipe material, and the length of the ground block L is given as

$$L=\frac{F_0}{\pi D\tau} \quad\cdots\cdots(3)$$

This length L gives the minimum size of the ground blocks leading to failure in the pipeline. In other words, the distance between two failures in the pipeline cannot be smaller than the value of L.

The above obtained quantity δ represents the deformable limit of this particular pipeline system. Therefore, we will name quantity δ to be obtained in a similar way, on the basis of the ground-block model, the "Deformability Index" of a pipeline system.

The procedure for determining the Deformability Index δ, and the value of L as well, will be different from the above example if the type of pipeline system is different. Examples of methods for evaluating different kinds of pipeline systems including jointed pipelines, such as bell-and-spigot type cast-iron pipeline systems, are illustrated in the Design Practices of Japan Gas Association (Abbrev. JGA)[16], and some of them have been presented by Saito el al.[17] (Evaluation of the "Deformability" of pipelines based on the ground-block model has already been adopted in the Design Practice mentioned above).

(2) Nonuiformity Index σ_A with respect to ground displacement

In this model of damage ratio prediction, the Nonuniformity Index, or the standard deviation of the ground displacement during earthquakes, will be estimated on the basis of damage statistics, as previously mentioned. We will give this newly defined Nonuniformity Index a symbol of σ_A rather than *NI*.

In this case, where the ground-block model is used, σ_A directly represents the degree of variation of seismic desplacement in ground blocks in the form of standard deviation. The subscript A pepresents the maximum acceleration (in units of cm/s^2 for example) at a certain area under consideration. The value of this acceleration does not necessarily have to be accurate as in a case measured by an accelerometer, but rather can be a rough value such as one estimated on the basis of an appropriate intensity scale of seismisity such as a JMA scale or MMI scale.

The magnitude of displacement in the ground is considered to be approximately proportional to the magnitude of acceleration. Therefore, if the Nonuniformity Index σ_{A1} is known for a certain type of ground condition and for a value of acceleration of A_1, the value of the Nonuniformity Index under an acceleration of A_2 can be predicted by applying the following equation :

$$\sigma_{A2}=\frac{A_2}{A_1}\sigma_{A1} \quad\cdots\cdots(4)$$

The quantity σ_A thus reflects the nonuniform nature of ground, which is typically represented by the irregularity of subsurface geology. At the same time, it contains information about the intensity of seismic ground motion.

The indices σ_A and *NI* are theoretically related in the case of an irregular surface layer, as will be related in section (4). The value of σ_A which is estimated on the basis of damage statistics, however, is determined without knowing the geological structure of a surface layer. Therefore, the index σ_A can be defined for any type of ground, which shows nonuniform behavior, as far as sufficiently accurate damage statistics can be obtained for the same type of ground. For example, this can be defined for the dynamic ground motion of liquefied ground, for which the mechanistic model has been proposed by the author and his colleagues[18),19)].

(3) Method for damage ratio prediction based on the indices, σ_A and δ

Let us assume that a pipeline system with a Deformability Index of δ [cm] is laid in a ground with a Nonuniformity Index of σ_A [cm]. Then the problem of predicting the damage ratio of this pipeline system is replaced by the problem of predicting the probability that the magnitude of relative displacement, Δu between two adjoining ground blocks exceeding the deformability Index, δ, of the pipeline.

We will make further assumptions to simplify the discussions. For exapmle, we will assume that the ground blocks move independently of each other and that the desplacement of ground blocks, u, forms a normal distribution with an average value of $\bar{u}$ and a standard deviation of σ_A.

Then the probability density of the displacements is expressed as

$$p(u)=N(\bar{u},\sigma_A)$$

The relative displacement Δu between two ground blocks, which are sampled randomly, is given by the form of probability density as

$$p(\Delta u)=N(0,\sqrt{2}\sigma_A)$$

It should be noted that this distribution function for Δu is independent of the value of the average displacement $\bar{u}$. It should also be noted that the actual movement of a ground block is not independent of movement in adjoining ground blocks. However, the actual distribution of Δu is expected to be closely ralated to the distribution based on the assumption of random sampling. Moreover, errors due to the above assumption are expected to be cancelled automatically when the value of σ_A is back-calculated on the basis of damage statistics and the above assumption about displacement distributions.

The probability of occurrence of damage is then given by integrating the above equation of probability density of Δu, as

$$P(\Delta u>\delta)=\int_\delta^\infty p(\Delta u)d\Delta u$$

The damage ratio can then be determined by multiplying the above probability by a factor C which represents the size of sample or the number of ground blocks constituting the sample set. If we define the damage ratio in terms of a unit of "number of damaged parts per pipe length of 1km", then the factor C is given as

$$C=\frac{1{,}000(m)}{L(m)}$$

where L is the size of the ground block.

We will call this factor the "sample-size factor", hereinafter.

Substituting $t=\Delta u/\sqrt{2}\sigma_A$ for the variable Δu in Eq. (4), the damage ratio ϕ is given in a normalized form as

$$\phi=CP(t>t_0)$$

$$=\frac{C}{\sqrt{2\pi}}\int_{t_0}^\infty \exp\left(-\frac{t^2}{2}\right)dt \cdots\cdots\cdots\cdots\cdots\cdots (5)$$

where

$$t_0=\frac{\delta}{\sqrt{2}\sigma_A}$$

Thus the damage ratio for any kind of pipeline buried under any ground conditions under an arbitrary earthquake motion intensity can be predicted by using Eq. (5) if the deformability characteristics, represented by the quantities δ and C, and the Nonuniformity Index of the ground, σ_A, are provided.

Inversely, the Nonuniformity Index σ_A for a certain type of ground condition can be estimated using the same equation if the damage ratio ϕ is provided,during an actual earthquake, for a certain kind of pipeline system of which the deformability characteristics, δ and C, are known. As previously mentioned, it is difficult to estimate the value of σ_A on the basis of geological information. Therefore, it will be the most convenient in estimating the value of σ_A to use the damage staitistics on pipelines obtained during past earthquakes.

(4) Relationship between the Nonuniformity Indices, σ_A and *NI*

Notwithstanding the above suggestion, most of the damage statistics have offered insufficient information on ground condtions. It will still be effective, therefore, to estimate the value of index σ_A from the value of index *NI* if geological infromation that is precise enough to calculate the value of *NI* can be obtained.

The index *NI* has been defined as the standard deviation of the expected magnitude of displacement, S_{Di} ($i=1\sim n$), in the surface layer (divided into ground blocks),in response to a unit intensity of earthquake motion, A_0, incident from the base ground (A_0=100cm/s^2 was assumed in the previous example shown in **Figs.1b and 2**).

In such a case, the average of maximum acceleration response of the surface layer, A_0' can be estimated by the following equation :

$$A_0'=\frac{A_0}{n}\sum_{i=1}^{n}S_{Ai}$$

where S_A is the average response acceleration of surface layer per unit incident acceleration of 1cm/s^2.

Acccording to the definition of σ_A, therefore, the

Table 1 Damage Ratios for Three Kinds of Gas Pipelines During Three Earthquakes (Classified According to Ground Conditions)

[unit: Amount of Damage/km]

Event (Place)	Miyagiken-oki. (Sendai)			Nihonkai-chubu		Loma Prieta
				Oga		
Kind of pipeline \ Type of Ground	Loamy Terrace and Gravel Layer	Alluvium and Peat	Residential Lands Developed in Hill and Valley Areas	Total Area	Liquefied Area	Marina District of S.F. (Liquefied Area)
Thread-Jointed Steel Pipeline	(9) 0.05	(14) 0.18	(181) 0.50	(14) 1.25	(11) 5.0	——
Mechanical-Joint, Cast-Iron Pipeline	(2) ——*	(2) ——*	(10) 0.027	(70) 2.27	(56) 9.1	——
Bell-and-Spigot, Cast-Iron Pipeline	——	——	——	——	——	(89) 11.1

Note: Figures in parentheses show the number of damaged parts.
Damage ratios for the *-marked parts are insignificant because the damage sustained was minimal.

index, NI, corresponds to the index, σ_A, under an acceleration of $A=A_0'$, and NI can be converted into σ_A through the following equation :

$$\sigma_A=\frac{A}{A_0'}NI$$

(Note : S_D and S_A are mutually convertible using a factor of $(T/2\pi)^2$.)

5. EXAMPLE OF ESTIMATING THE NONUNIFORMITY INDEX σ_A

Damage statistics of gas distribution pipelines, obtained during three earthquakes, will be used to estimate the value of the Nonuniformity Index σ_A for several types of ground conditions. These three cases alone give data classified according to the kind of pipeline system.

The name of the three earthquakes, the places of these events, and the intensity of the earthquakes in terms of maximum acceleation are as follows :

1. 1978 Miyagiken-oki EQKE., Sendai, Japan, $A=275\text{cm/s}^2$
2. 1983 Nihonkai-chubu EQKE., Oga, Japan, $A=250\text{cm/s}^2$
3. 1989 Loma Prieta EQKE., Marina District, San Francisco, U.S.A., $A=250\text{cm/s}^2$

The value of acceleration at Sendai is based on Tamura[20] who estimated it at 250-300cm/s^2. Those at Oga and the Marina District are based on reports from JSCE[21] and the Association for Development of Earthquake Prediction[22], respectively.

It should be noted that damage to pipelines in both Oga and the Marina District was mostly due to soil liquefaction. Both areas had a common feature in that the ground was almost flat, which meant that no remarkable lateral spreading of the ground was observed.

(1) Damage statistics during the three earthqukaes

The damage ratios for three kinds of pipelines, classified in accordance with the types of ground conditions are listed in **Table 1**. The statistcs for Sendai and Oga were cited from reports prepared by JGA[23),24)], and the statistics for the Marina District were cited from the same report as Ref. 22. Data for the liquefied area of Oga, in **Table 1** was estimated assuming that the liquefied area formed 20% of the total area supplied with gas, and assuming that 80% of total amount of damage was sustained by the liquefied areas.

Table 1 shows the remarkable fact that the damage ratio varies greatly depending on the kind of pipeline although the type of ground may be the same. For example, the damage ratio for thread-jointed steel pipelines in developed land in hilly areas is almost twenty times as much as that for cast-iron pipelines with mechanical joints. The damage ratios for Oga show the reverse tendency, indicating that the damage ratio for cast-iron pipelines is almost twice as much as that for steel pipelines. The proposoed method of damage ratio prediction must properly explain these facts to prove its rationality.

(2) Deformability charcteristcs (δ and C) of damaged pipelines

The Deformability Indices, δ, and the sample-size factors, C, for the three kinds of damaged pipelines, listed in **Table 1**, are as listed in **Table 2**. Although these indices are calculated using the ground-block model shown in **Fig.3** , the detailed procedure of the calculation will be left to the Refs. 14 and 16 because of the shortage of remaining space. For the dimensions and properties of the pipes and joints as well as for the recommended values for soil restrictions against pipelines, to be

Table 2 Deformability Characteristics of Three Kinds of Pipelines

Kind of Pipeline (Type of Joint)	Deformability Index δ [cm]	Sample-Size Factor C (L [m])	Remarks (Average Diameter)
Thread-Jointed Steel Pipeline	2.7	32 (31.6)	(Nominal Dia.) 50 mm
Mechanical-Joint, Cast-Iron Pipeline	4.5	200 (5)	150 mm
Bell-and-Spigot, Cast-Iron Pipeline	2.6	64 (15.6)	150 mm

Table 3 Nonuniformity Indices of Sustained Ground Based on Damage Ratio Statistics, σ_{275} [unit: cm]

Place	Sendai			Oga		Marina District
Kind of pipeline \ Type of Ground	Loamy Terrace and Gravel Layer	Alluvium and Peat	Residential Lands Developed in Hill and Valley Areas	Total Area	Liquefied Area	Liquefied Area
Thread-Jointed Steel Pipeline	0.64	0.75	0.88*1	1.19	2.08*3	—
Mechanical-Joint, Cast-Iron Pipeline	—	—	0.88*2	1.54	2.07*4	—
Bell-and-Spigot, Cast-Iron Pipeline	—	—	—	—	—	2.16*5

used for the calculations, refer to the "Recommended Practice of Earthquake-Resistant Design" of JGA[16].

Table 2 indicates that the difference in the value of δ between thread-jointed steel pipe and bell-and-spigot type cast-iron pipe is very small. However, the values of C show a difference two times as great. The mechanical-join type cast-iron pipe uses a rubber ring to secure gas sealing. This allows a large displacement of the joint while keeping gas-tightness, which in turn gives a large value of δ to the pipeline. However, because this joint does not use a stopper on the pipe spigot, the force on a joint is not transferred to, and shared by, the next joint. This results in a very small value of L, as small as 5m, which is the average distnace between the joints. As a result, the sample-size factor C for this cast-iron pipe becomes very great.

Again, the proposed method of damage ratio prediction must properly explain the damage statistics, while taking into account the above indicated differences in deformability characteristics between the different kinds of pipeline systems.

(3) Estimated values of σ_A and discussion

The estimated values of σ_A based on the data of both **Table 1** and 2, and using Eq. (5), are listed in **Table 3**. The values of σ_A are expressed in a unified mode, namely, as the Nonuniformity Index at the same acceleration of $A=275\text{cm/s}^2$, which represents the seismic intensity at Sendai during the Miyagiken-oki Earthquake.

The following remarkable facts can be discerned from **Table 3**.

(1) Theoretically, the Nonuniformity Index for a certain type of ground condition should take a single value regardless of the type of pipeline, if the model is reasonable.

The obtained results prove the rationality of the proposed model in that the calculate values of σ_{275} for both thread-jointed steel pipeline and mechanically-jointed cast-iron pipeline in ground developed for residence are exactly the same (compare the figures maked with *1 and *2).

The values of σ_{275} obtained for the same two kinds of pipelines in the liquefied ground of Oga are almost the same too, thus proving again the rationality of proposed model (compare the figures marked with *3 and *4).

(2) The values of σ_{275} for the liquefied ground of both Oga and the Marina District are very similar although the deformability characteristics of the pipelines in both areas were fairly different (compare the figures marked with *3 , or *4, with those marked with *5).

This fact is likely to further support the proposed model.

(3) The numerical order for the values of σ_{275} perfectly corresponds with that for the damage ratios, although this may be taken to be quite a

Table 4 Classification of Ground Conditions Based on σ_{275} (A Porposal)

Degree of Nonuniformity	σ_{275} [cm]	Remarks (Corresponding Ground Conditions)	Examples from Existing Ground and Estimated Values of σ_{275}
Very Uniform	< 0.5	Stiff diluvial deposit: Rock Mass	
Uniform	0.5 ~ 0.7	Moderately stiff diluvial deposit: Gravel Layer: Alluvium with a uniform thickness	Old downtown area of Sendai City (~ 0.6) Alluvial plain east of Sendai (~ 0.7)
Somewhat Nonuniform	0.7 ~ 1.0	Alluvium with a somewhat nonuniform thickness: Alluvial fan: Ordinary residential land developed in a hilly area	Nagamachi-Kohriyama District of Sendai (0.8 ~ 0.9) Shiogama City (Total area) (~ 1.0)
Very Nonuniform	1.0 ~ 1.5	Alluvium with an extremely nonuniform thickness such as a river basin or drowned valley: Areas with liquefiable ground to some extent: Land developed by cutting hills and filling valleys on a vast scale	Oga City (Total area) (~ 1.2) Nanko-dai (Housing area), Sendai (~ 1.5)
Extremely Nonuniform	1.5 <	Very soft alluvium with an extremely nonuniform thickness: Areas mostly consisting of liquefiable ground	Port South District of Shiogama (~ 2.4) Concentrated-liquefaction area of Oga (~ 2.1) Noshiro City (Total area) (~ 2.2) Marina District, S.F. (~ 2.2)

natural result.

In praticular, the Nonuniformity Index for liquefied ground is shown to take extremely large values compared with ordinary (nonliquefied) ground. This fact suggests that the dynamic model of partially (or locally) liquefied ground, which has been proposed by the present author [18),19)], can be properly used to explain the great magnitude of strain to be produced in the ground, and subsequent high damage ratio resulting from soil liquefaction.

6. EXAMPLES OF THE PRACTICAL APPLICATIONS OF THE PROPOSED METHOD

(1) Classification of ground conditions based on the Nouniformity Index σ_A

As previously mentioned, evaluation of the vulnerability of existing pipelines is essential to establish effective countermeasures against earthquakes. For this purpose, the proposed method of damage ratio prediction will provide the most practical, as well as the most reasonable tool.

In order to apply this tool practically, quantitative classification of the ground conditions by the Nonuniformity Index σ_A is necessary. This is possible by referring to the above obtained results (i.e. **Table 3**) and the damage statistics for the other areas and during the other earthquakes, such as shown in Ref. 13.

Table 4 gives an example of the classification of ground conditions with a value of σ_{275}.

Using the values of σ_{275} thus given, on the one hand, and knowing the defomability characteristics of pipelines, i.e. the Deformability Index δ and the sample-size factor C, on the other, we can predict the possible values of damage ratio while taking the three fundamental factors into account.

(2) Acceleration dependence of the damage ratio of cast-iron pipeline

Kubo et al.[2)] have established a relationship between the ground acceleration and the damage ratio of cast-iron pipelines on the basis of the local distribution of damage to water distribution pipelines in the suburbs of Los Angeles during the 1971 San Fernando Earthquake. Their study is summarized in **Fig.4.** A similar relationship between acceleration and damage ratio was obtained using the proposed method, and the results are shown in the same figure.

In the latter study, the pipeline was assumed to be the same type, both in terms of joint and average diameter, as that used in Tokyo during the 1923 Kanto Earthquake, as well as in the Marina District of San Francisco during the 1989 Loma Prieta Earthquake. This is based on the fact that the same U.S. standard of pipe material and pipeline systems were used for both water distribution and gas distribution in the early 20th century, both in the United States and in Japan. Therefore, the same data of bell-and-spigot (filled with lead and yarn) joints as that listed in **Table 2** was used to determine the deformability characteristics with only slight modification. This modification was based on the fact that water is less apt to leak than gas even though the degree of looseness in the joint may be the same. Taking this fact into account, the following values for δ and C could be determined

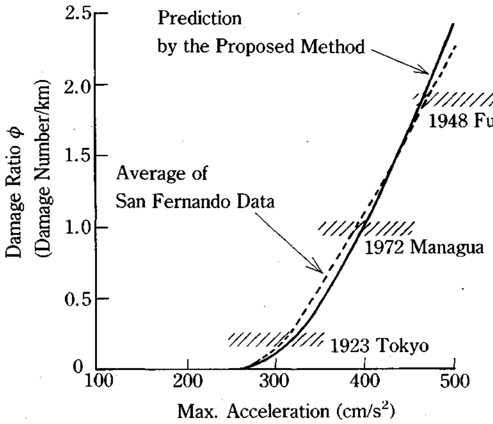


Fig.4 Relationship Between the Damage Ratio of Cast-Iron Water Pipelines and Maximum Ground Acceleration (Compariosn of Prediction Based on the Proposed Method with San Fernando Data[2])

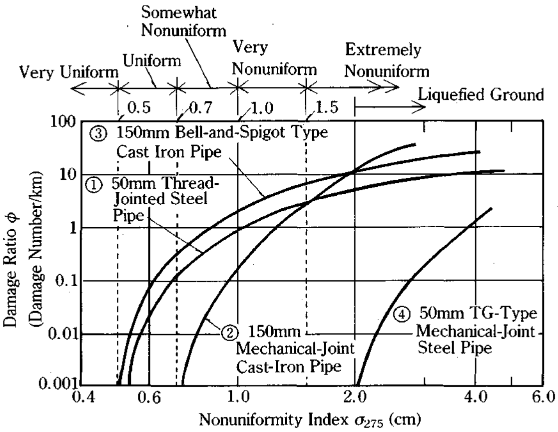


Fig.5 Relationship Between the Damage Ratio and the Nonuniformity Index for Four Kinds of Pipleine Systems (Max. Ground Acceleration is Assumed to be $A=275\text{cm/s}^2$)

(Ref. 14).

$\delta=3.0\text{cm}$ $C=55(L=18\text{m})$

As for ground conditions in the suburbs of Los Angeles, no data was presented by Kubo et al[2]. It is most reasonable, however, to assume the most common condtions for residential lands that can be classified between the "uniform" ground and the "somewhat nonuniform" ground referring to **Table 4**. Accordingly, the following value was assumed for the Nonuniformity Index :

$\sigma_{275}=0.70\text{cm}$

The ϕ-A relationship in **Fig.4** , based on the proposed method,was calculated by Eq.(5) using the above three figures. The value of σ_A for the arbitrary intensity of acceleration A was determined by Eq.(4) substituting σ_{275} for σ_{A1}, and 275 for A_1.

The agreement between the two curves of the ϕ-A relationship is most remarkable ; the both curves give almost the same value of acceleration of about 250cm/s^2 at the initiation of damage occurrence, while the shapes of the curves are also very similar.

It should be noted, however, that the curve of the ϕ-A relationship necessarily deviates from the above obtained curve if a different kind of pipeline system, with different deformability characteristics, is considered. This deviation can properly be predicted by the proposed method of damage ratio prediction, while no other methods like this one have yet been proposed.

(3) Application to the evaluation of the earthquake resistance of pipeline systms

The quantitative evaluation of the degree of vulnerability, or probable damage ratio of pipeline systems, is almost equivalent to the evaluation of earthquake resistnace.

In this section, the effect of ground conditions on the degree of vulnerability of four kinds of pipeline systmes with differect deformability characteristics will be evaluated by applying the proposed method.

The intensity of earthquake ground motion is assumed to be $A=275\text{cm/s}^2$, which is equal to the intensity at Sendai during the 1978 Miyagiken-oki Earthquake.

Three of the four kinds of pipeline systems will be the same as those already shown in **Tables 1** and **2**, namely :

① thread-jointed steel pipelines, 50mm in diameter

② mechanical-joint cast-iron pipelines, 150mm in diameter

③ bell-and-spigot cast-iron pipelines, 150mm in diameter

④ mechanical-joint steel pipelines, 50mm in diameter, which is currently in use in the Tokyo Metropolitan Area. The joint is equipped with a stopper, which prevents the pipe from slipping out of the socket with a strong resisting force until a considerable amount of displacement between the socket and pipe occurs. The deformability Index and the sample size factor are given as

$\delta=12.3\text{cm}$ and $C=84$,

respectively, referring to the load-displacement relationship of the joint presented in the Design Practice of JGA[16] (or Refs. 13 and 14).

The damage ratios were calculated for varying values of σ_{275}, and the results of calculations are as shown in **Fig.5**

This figure indicates that both pipeline systems, ① and ③, show the possibility of sustaining a substantially high ratio of damage even in ground classified as "uniform". The damage ratio of the pipeline system ② is lowered substantially under "somewhat nonuniform" and "uniform"ground condtions owing to the improvement in the Deformability Inedx, δ. The damage ratio of the same pipline system, however, increases rapidly as the nonuniformity of the ground increases ; and it becomes even higher than in the pipeline systems ① and ③, in the "extremely nonuniform" ground, such as liquefied ground. This reversal of the damage ratio values due to the degree of nonuniformity in the ground corresponds very well to the actual tendency of damage shown in **Table 1**.

For reference, a pipeline of less importance, such as a low pressure pipeline with a small diameter, can be evaluated as "sufficiently earthquake-resistant" if its expected damage ratio is smaller than about 0.01. In that case, the number of damaged parts becomes less than 1 per 100km of pipeline. This level of damage ratio is comparable to that with which the gas industry deals in its daily maintenance of pipeline networks. For example, no exceptional damage would be expected in the Marina District during the 1989 Loma Prieta Earthquake, if the damage ratio were less than 0.01.

Thus the pipleine system ② is sufficiently earthquake-resistant as long as it is laid in ordinary ("somewhat nonuniform" or better) ground. However, it is judged to be nonearthquake-resistant in ground with a higher degree of nonuniformity.

The above reversal of the order of magnitude of the damage ratio due to a change in the value of the Nonuniformity Index can be explained by taking into account the nature of Eq.(5). Namely,if we consider the limit state where the value of σ_A becomes great and the quantity $t_0 = \delta/\sqrt{2}\,\sigma_A$ approaches zero, then the value of ϕ approaches $0.5C$, which is the function of sample-size factor C alone, without having any relation with the value of δ. Actually, the value of C in pipeline system ② is about three times as great as that in pipeline system ③. This explanis the above reversal of the damage ratios.

Pipeline system ④ is shown to be sufficiently earthquake-resistant even in "extremely nonuniform" ground, which may have a value of σ_{275} as great as 2.5cm. This implies that this pipeline system can be used safely in liquefiable ground as long as landslides or large scale lateral spreadings due to liquefaction does not occur.

Thus the proposed method of damage ratio prediction can be used as a tool to evaluate the earthquake resistance of new pipeline systems, as well as old ones.

7. CONCLUSIONS

The proposed method of seismic damage-ratio prediction of pipeline systems has been formed by expressing quantitatively the relationship between three fundamental factors,which contribute to the vulnerability of pipelines,and by using simple models of ground displacement and ground-pipeline interaction.

This method can be regarded as being based on definite mechanistic models rather than on the statistical methods hitherto proposed, which put causal relationships into a black box.

The first factor, namely, the nonuniformity of the seismic ground displacement, is related to the irregularity of the geological structure of surface layers, in general. However, this study showed that the nonuniformity of ground displacement, as a result of soil liquefaction, is expressed in the same terms as the "Nonuniformity Index" of ground displacement.

Secondly, ground displacement can be regarded as being approximatley proportational to the seismic intensity or acceleration. Therefore, the method takes into account seismic intensity by applying the Nonuniformity Index.

As for the third factor, the ground-block model makes the evaluation of the "deformability" of pipeline systems easy and practical. The deformability characteristics can be estimated on the basis of the data on the load-displacement relationship, and some tests on the soil properties.

The study on the Nonuniformity Index of the ground based on damage statistics did not reveal any inconsistencies, but rather proved the proposed method to be reasonable. Thus the proposed method of damage ratio prediction can be used to present the information essential to establishing earthquake countermeasures.

The zonation of the various types of ground based on the Nonuniformity Index will be most effective for this purpose. The reliability of earthquake-resistant design of pipeline systems will thus be further enhanced by using the proposed method.

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地盤変位の不均一性にもとづく埋設管の地震被害率予測法とその応用

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地盤条件（液状化を含む）と地震動の強さによって定まる地盤の動的変位の不均一度指数と，管の種類に対して定まる配管系の地盤変位吸収能力を組み合わせた，埋設管の地震被害率予測法を提案する．また，過去の地震における埋設管の被害統計をもとに各種の地盤の不均一度指数を逆算し，本提案の有効性を検証する．その結果をもとに，埋設管系の被害率の予測と耐震性の評価に提案した手法を応用する事例を示す．