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著者	Kitaura Masaru, Miyajima Masakatsu
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Response Simulation of Buried Pipeline During Soil Liquefaction

Masaru KITAURA* and Masakatsu MIYAJIMA*

This paper deals with the behavior of buried ductile iron pipelines during liquefaction. Quasi-static analyses are carried out by employing a simple liquefaction model. A pipeline is modeled as a series of segmented Winkler beams connected longitudinally by joints with springs for both axial and bending motions. The modified transfer matrix method is used for numerical calculations.

The results show that the probability of failure of a buried pipe due to the bending around joints is very great, since the pipeline is allowed to be floating during soil liquefaction. On the other hand, the probability of failure of a pipeline due to pipe bending is high in cases where the large spring constants for joint rotation are involved. Through these analyses, it becomes clear that the pipeline response is very sensitive to the evaluation of the equivalent soil spring constant. It is thus emphasized that the nature of the equivalent soil spring constant must be made clear quantitatively.

1. Introduction

Buried pipelines have been widely used in the distribution systems for water, gas and sewerage, and recently they are also used for conveying fuel, telecommunications and so on. Much damage due to past severe earthquakes reveals that buried pipelines are vulnerable to ground failure. In spite of much studies of the buried pipelines, quantitative analysis of damage to pipelines has been rare. The following is a brief review of current researches regarding theoretical analyses of the buried pipelines[1].

Sakurai[2] carried out a quasi-static analysis on buried ductile iron pipelines modeled as beams on an elastic foundation, which were connected by joint springs longitudinally. In the paper, axial deformations of the pipeline were computed by the stiffness matrix method when a seismic force acted on the pipe through non-linear soil springs. Takada et al.[3] also simulated the behavior of a buried polyvinyl chloride pipeline using the models similar to that of Sakurai[2]. Taking into consideration the rotation of joints, both axial and transverse motions of the pipeline were treated. Kitaura et al.[4] analyzed the behavior of saturated loose sand layers in Niigata earthquake and computed the response of buried pipelines by employing the finite element method with non-linear effective stress analysis.

This paper deals with the behavior of buried ductile iron pipelines during soil liquefaction. The liquefaction of sandy soil caused much damage to the buried pipeline systems, for example, in the 1964 Niigata earthquake and in the 1983 Middle Japan Sea earthquake. Therefore, it is of crucial importance to understand the dynamic response of the buried pipelines during soil

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* Department of Construction and Environmental Engineering

liquefaction. The analytical model for the pipeline adopted in the present study is similar to that of Takada³⁾, while this paper is employing a simple liquefaction model in evaluating the response.

2. Response Analyses of Buried Pipelines

2.1 Analytical model

Fig. 1 shows the analytical model of the buried pipelines used in the present study. It is the same as that proposed by Takada³⁾ and is based on the following assumptions:

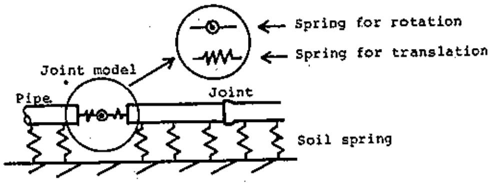

Fig. 1 Analytical model³⁾.

1) Quasi-static analyses are postulated, i. e. the effects of inetia force and damping are assumed to be negligible.
2) Buried pipelines are treated as a series of segmented elastic beams connected longitudinally by joints which have the function of a spring for both axial and bending motions. Each beam is supported by a Winkler foundation.
3) The pipe motions are analyzed in the two dimensional horizontal plane.
4) The perfect elastic behavior is assumed for the pipe material.

2.2 Equations of motion

Let u and v be the longitudinal and transverse displacement of the pipe and let U and V be those of the free field, respectively. Then, the basic differential equations governing the motion of a buried pipe can be established as follows:

$$-EA\frac{d^2u}{dx^2}=K_u(U-u) \qquad \text{: for the longitudinal motion} \qquad (1)$$

$$EI\frac{d^4v}{dx^4}=K_v(V-v)+F \qquad \text{: for the transverse motion} \qquad (2)$$

where E = Young's modulus of the pipe material, A = cross-sectional area of the pipe, I = area moment of inetia of the pipe, K_u, K_v = equivalent spring constants for longitudinal and transvers motions, respectively, which reflect the soil-structure interaction and F = force caused by the buoyancy and groundwater flow during soil liquefaction.

2.3 Modified transfer matrix method

In order to solve the basic differencial equations, Eqs. 1 and 2, modified transfer matrix method improved round off errors presented by Nakamura⁵⁾ is employed in the present study. In this method, the relationship of a given physical quantity between two points is transferred. This method is much better than the traditional transfer matrix method because the round off errors in this method is very small.

Using the notation $' = d/dx$, Eq. 1 can be rewritten as:

$$\frac{d}{dx}\begin{Bmatrix} u \\ w \end{Bmatrix} = \begin{bmatrix} 0 & 1 \\ K_u/EA & 0 \end{bmatrix} \begin{Bmatrix} u \\ w \end{Bmatrix} + \begin{Bmatrix} 0 \\ -K_u \cdot U/EA \end{Bmatrix} \tag{3}$$

The recurrence formula of Eq. 3 can be expressed as:

$$\begin{Bmatrix} u \\ w \end{Bmatrix}_{x+\Delta x} = \begin{bmatrix} 1 & \Delta x \\ K_u \cdot \Delta x/EA & 1 \end{bmatrix} \begin{Bmatrix} u \\ w \end{Bmatrix}_x + \begin{bmatrix} 1 & \Delta x \\ K_u \cdot \Delta x/EA & 1 \end{bmatrix} \int_0^{\Delta x} \begin{bmatrix} 1 & s \\ -K_u \cdot s/EA & 1 \end{bmatrix} \begin{Bmatrix} 0 \\ -K_u \cdot U/EA \end{Bmatrix} ds \tag{4}$$

In the same manner, Eq. 2 for the transverse motion can be rewritten as:

$$\begin{Bmatrix} v \\ v' \\ v'' \\ v''' \end{Bmatrix}_{x+\Delta x} = \begin{bmatrix} 1 & \Delta x & \Delta x^2/2 & \Delta x^3/6 \\ 0 & 1 & \Delta x & \Delta x^2/2 \\ 0 & 0 & 1 & \Delta x \\ -K_v \cdot \Delta x/EI & 0 & 0 & 0 \end{bmatrix} \begin{Bmatrix} v \\ v' \\ v'' \\ v''' \end{Bmatrix}_x +$$

$$\begin{bmatrix} 1 & \Delta x & \Delta x^2/2 & \Delta x^3/6 \\ 0 & 1 & \Delta x & \Delta x^2/2 \\ 0 & 0 & 1 & \Delta x \\ -K_v \cdot x/EI & 0 & 0 & 1 \end{bmatrix} \int_0^{\Delta x}$$

$$\begin{bmatrix} 1 & -s & -s^2/2 & -s^3/6 \\ 0 & 1 & -s & -s^2/2 \\ 0 & 0 & 1 & -s \\ K_v \cdot s/EI & 0 & 0 & 1 \end{bmatrix} \begin{Bmatrix} 0 \\ 0 \\ 0 \\ (K_v \cdot V + F)/EI \end{Bmatrix} ds \tag{5}$$

From Eqs. 4 and 5, the field matrix F can be expressed as:

$$F = \begin{bmatrix} 1 & 0 & 0 & -D \cdot C & 0 & 0 \\ 0 & 1 & -D & 0 & D^2 \cdot B/2 & D^3 \cdot B/6 \\ 0 & 0 & 1 & 0 & -D \cdot B & -D^2 \cdot B/2 \\ -D \cdot \bar{K}_v & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & D \\ 0 & -D \cdot \bar{K}_u & 0 & 0 & 0 & 1 \end{bmatrix} \tag{6}$$

where $B = EI/E_0I_0$, $C = EA/E_0A_0$ and $D = \Delta x/l_0$. $\bar{K}_v$ and $\bar{K}_u$ are non-dimensional equivalent spring constants, respectively.

The buried pipelines are assumed here to be connected by springs for translational and rotational movements at the joints (see Fig. 2). The equiliburium equations governing the deformations and forces at the joints are also indicated in Fig. 2. The point matrix P corresponding to the situation defined in Fig. 2 can be obtained as:

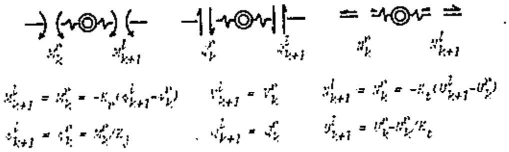

Fig. 2 Equilibrium equations at joint[3].

$$P = \begin{bmatrix} 1 & 0 & 0 & -1/K_l & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & -1/K_j & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix} \qquad (7)$$

2.4 Simplified liquefaction model

The forces due to the buoyancy and groundwater flow besides seismic motion act on the buried pipelines during soil liquefaction. During the complete liquefaction, the seismic motion is believed to have a relatively little influence on the buried pipelines, because the shearing waves transmitting the ground become less as the ground becomes softer. In contrast, the groundwater flow have a great influence on the buried pipelines, especially at the weak surface ground where the phenomenon of sandblow often occurs. However this phenomenon seems to occur only locally. Therefore, in the present analyses, the effect of the groundwater flow is ignored for simplicity.

In general, the weight per unit volume of a water-supply pipe filled with water is known to lighter than that of liquefied soil. Fig. 3 shows the ratio of buoyancy acting on a ductile iron pipe during soil liquefaction to the weight of a filled with water. This figure proves that the ratio of the buoyancy to the self-weight is 130% or so, irrespectively of the nominal diameter. This means that the probability of pipe floating during liquefaction is great in water supply systems. Therefore, only the effect of buoyancy on the buried pipeline is taken into account in the presest analysis described below. In the present analyses, it is also assumed that the duration time of liquefaction is long enough, that is, quasi-static analyses is carried out for the pipelines buried in the completely liquefied soil.

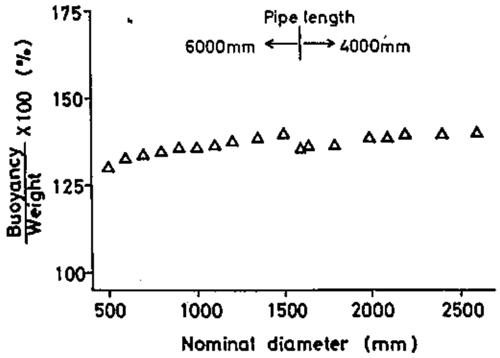

Fig. 3 Buoyancy per unit weight of a water supply ductile iron pipes.

3. Numerical Computation and Results

Table 1 shows dimensions of the ductile iron pipe which is used in water supply systems[6]. In the following numerical calculation, 20 pipes are connected by 19 corresponding joints. One end of the pipeline is assumed to be fixed at a building and the other to be free.

Fig. 4 shows the state that the force due to pipe floating acts on the pipelines step by step. The distributed load, which is equivalent to the difference between the weight per unit volume of liquefied soil and that of the water supply ductile iron pipe filled with water, acts on the pipeline

Table 1 Dimensions of pipe

	Ductile cast iron
Outside diameter (cm)	52.9
Thickness (cm)	0.95
Young's modulus (kg/cm²)	1.6×10^6
Length (cm)	500
Specific gravity	7.15

(1kg/cm² = 98KN/m²)

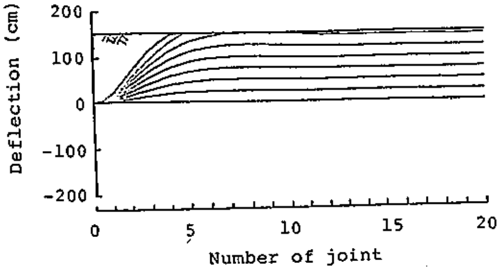

Fig. 4 Floating of pipe.

as the effect of buoyancy. The present analyses are calculated for 10 steps in increment loaded method. The curves in Fig. 4 indicate the deflection of the pipelines acted the corresponding load steps. Fig. 5 indicates the relationships between equivalent soil spring constants and the pipeline responses during soil liquefaction. The displacement of joint-slip is assumed to be as follows. When a pipeline is floating, the maximum displacement of the pipe Δ is given as (see Fig. 6):

$$\Delta=\sqrt{(v_2-v_1)^2+L^2}-L \tag{8}$$

The half of this value is assumed to be equal to the joint-slip of both ends of the pipe. Fig. 5 indicates that the pipeline response increases as the equivalent soil spring constant degreases, that is, the degree of liquefaction increases. The angle of joint rotation is larger than the allowable value when the equivalent soil spring constant is 2×10^{-5}kg/cm²(1.96×10^{-3} KN/m²) or so. However, the displacements of joint-slip and bending moment are smaller than the allowable

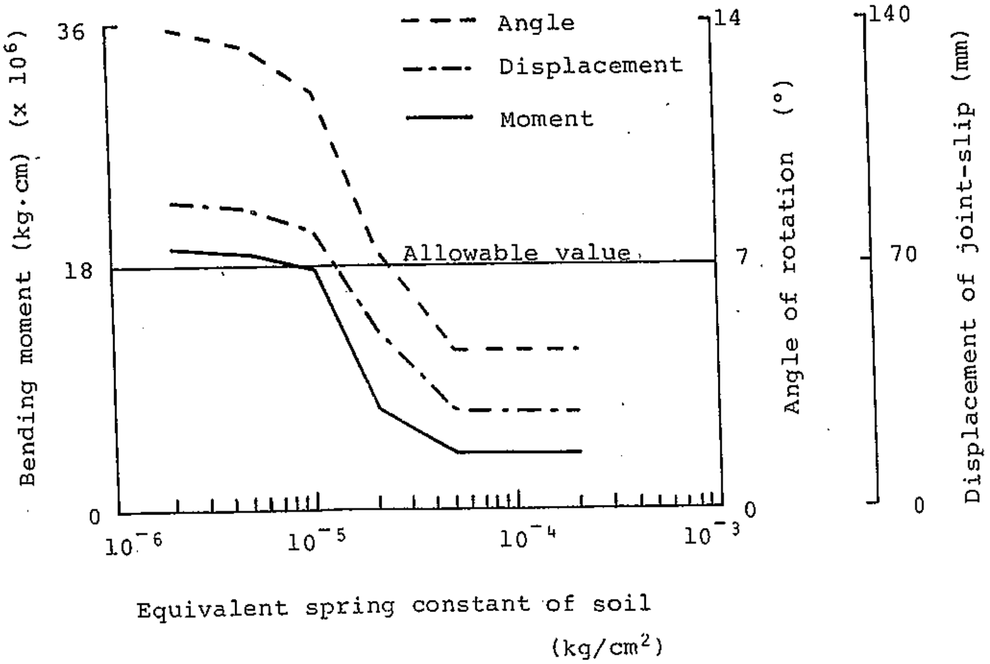

Fig. 5 Relationships between equivalent spring constant of soil and responses of buried pipe.

values, respectively. Fig. 7 shows the final deflection of the pipeline. In this case, as the equivalent soil spring constant is 1×10^{-5}kg/cm^2(9.8×10^{-2} KN/m^2), it is found that all the pipeline responses are over the corresponding allowable values (see Fig. 5). It shows also that the pipe itself has small deflection because of large pipe rigidity, while the joint bending is very large. This means that the probability of failure due to joint bending is very high when the pipeline is floating during soil liquefaction.

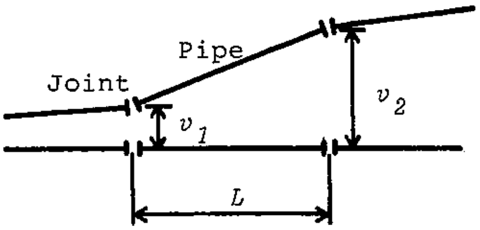

Fig. 6 Schematic diagram of buried pipes.

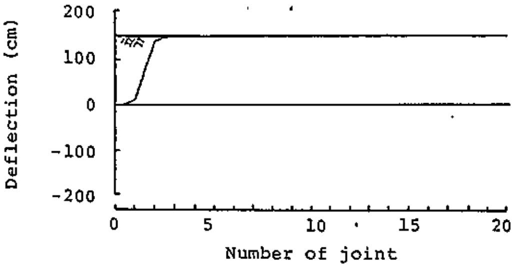

Fig. 7 Final deflection of pipe.

In the present numerical calculations, it is revealed that the pipeline response is very sensitive to the evaluation of the equivalent soil spring constant (see Fig. 5). Fig. 8 shows the relationship between the value of the standard penestration resistance, i. e. N value and the equivalent soil spring constant7). The N value of the liquefied soil is anticipated to be nearly equal to zero, while it has not yet been verified. Therefore, in order to assess more accurately the pipeline response during soil liquefaction, it is necessary to make it clear quantitatively.

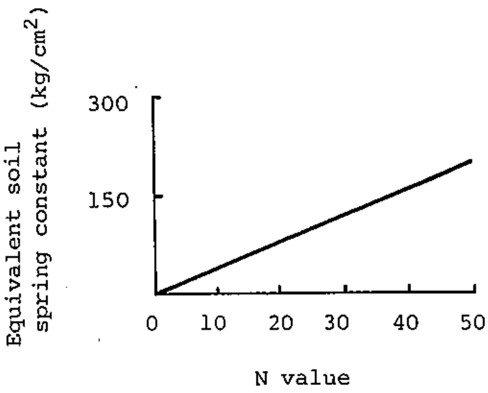

Fig. 8 Relationship between N value and equivalent soil spring constant

Fig. 9 illustrates the relationships between the spring constant for joint rotation and the pipeline response during soil liquefaction. It is seen that the pipe floating is mitigated as the spring constant for joint rotation is increased, that is, the pipeline becomes rigid. On the other hand, the capability of absorbing the bending moment at the joint decreases as the spring constant for joint rotation is decreased. Fig. 9 also reveals that, in case of the large spring constant for joint rotation, both the angle of joint rotation and the displacement of joint-slip are smaller than the allowable value, respectively, and that the bending moment is larger than the allowable value. Therefore, the probability of failure due to pipe bending is judged to be high in case of pipes with the large spring constant for joint rotation.

4. Further Studies Needed

As shown above, the results of these analyses can reveal the pipeline response qualitatively.

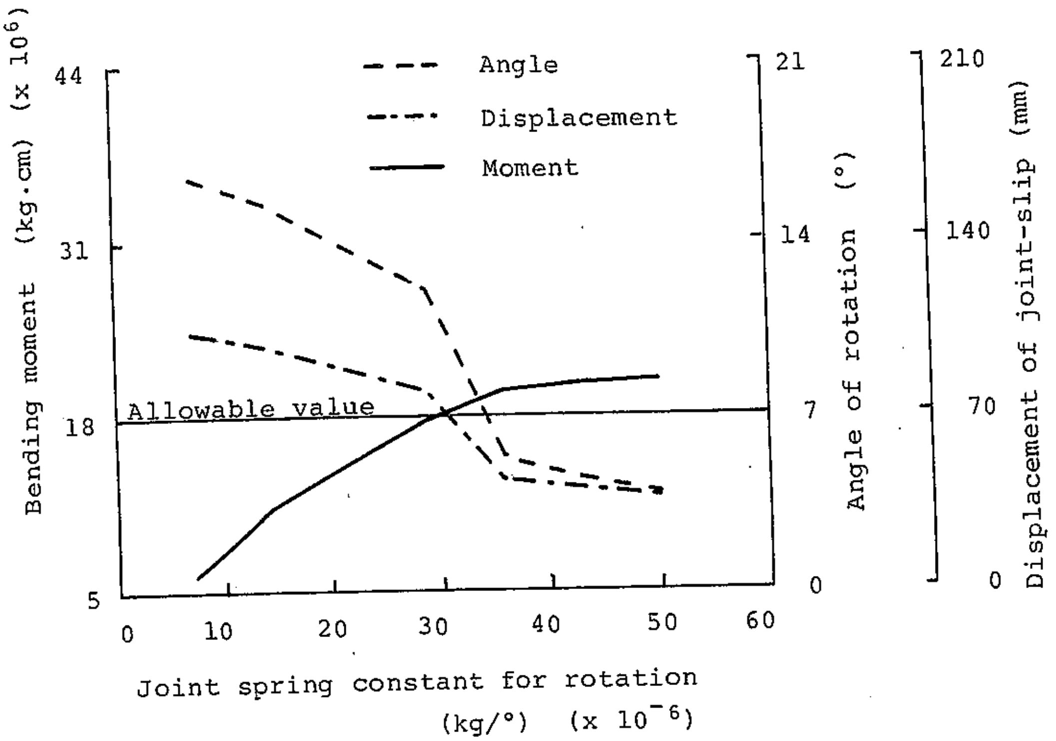

Fig. 9 Relationships between spring constant for rotation and responses of buried pipe.

However, several major problems remain to be solved, for example, the evaluation of equivalent soil spring constant during soil liquefaction, the effect of groundwater flow on the pipeline and pipeline response during incomplete liquefaction, etc. It is important to make them clear in order to predict more accurately the pipeline behavior during soil liquefaction.

5. Conclusions

Quasi-static analyses have been carried out by employing a simplified liquefaction model, together with a pipeline model which consist of a series of segmented Winkler beams connected longitudinally by joints with springs for both axial and bending motions. The modified transfer matrix method has been used for the numerical calculations. The summary of above results will be described below.

The probability of failure of a pipeline due to joint bending is very high as the pipeline is forced to be floating during soil liquefaction. On the other hand, in case of pipelines with the relatively large spring constants for joint rotation, the influence of pipe floating is mitigated, while the probability of failure due to pipe bending becomes higher. In the present numelical calculations, it is found that the pipeline response is very sensitive to the evaluation of the equivalent soil spring constant. Therefore, it is necessary to assess more accurately the equivalent soil spring constant.

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