EARTHQUAKE RESISTANT DESIGN OF UNDERGROUND PIPELINES

by

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SYNOPSIS

The dynamic behaviour of underground pipelines which are allowed to slide during earthquakes is studied. This sliding is resisted by friction between the pipe and surrounding ground. Model experiments were performed to determine the characteristics of non-linear friction forces. The analytical solution is also deduced to obtain the relative displacement between the pipe and the ground, making use of the results of the experiments.

From the results of this study, the necessity of flexible joints in pipe lines which absorb the relative displacement is emphasized to assure earthquake proofness by harmonizing the pipelines to the behaviour of the surrounding ground.

INTRODUCTION

Earthquake resistant design of structures such as gas-pipes, water-pipes, subway tunnels and so forth can be classified as the same from the view point of the seismic response analysis, because such structures are constructed beneath the ground surface and they constitute network systems. Since an under ground pipeline is a long,continuous system, it is necessary to consider the out of phase motion of the surrounding ground as the seismic disturbance moves along the pipelines. It has been made clear to date that the velocity at which the seismic disturbance propagates is a very important factor in an earthquake resistant design of pipelines. Moreover, existence of friction forces between the pipe and ground makes the problem more complicated.

Formerly, the authors[1] showed that the axial strain amplitude induced in tubular structure during strong motion earthquakes of 200-300 gals is not less than the order of 10^{-3}, assuming no slip on the contact plane between the pipe and ground. The axial force in the structure corresponding to a strain of the order of 10^{-3} would be larger than the friction force on the contact plane. During earthquakes, it is quite possible that sliding of the pipe could occur, prior to yielding at a strain of the order of 10^{-3}.

Earthquake resistant design of pipelines considering the sliding characteristics has not yet been established.[2,3,4] The main objective of this paper is to determine the characteristics of this non-linear friction force on both static and dynamic cases and to solve the differential equation that governs the behaviour of the system and to obtain the analytical solution of the relative displacement between the pipe and ground.

EXPERIMENTS ON RESTORING FORCE

A simple diagram of the model is shown in Fig.1. In this experiment, the similarity laws covering the model and prototype were not considered, because attention was restricted to the properties of the restoring force

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between the structure and the surrounding soil. Only the properties of the model materials were considered. Dry sand was used as a model ground whose uniformity coefficient was 2.0. The pipe model was an aluminum pipe whose diameter and length were respectively 55mm and 2000mm. The earthpressure acting on the crown of the pipe was controlled using the vertical weighting devices shown in Fig.1. The sand was sufficiently consolidated by mechanical vibration.

The experiment was carried out for the following two cases; a) static test and b) dynamic test. For case a) a forced displacement was imposed manually in the axial direction, changing the displacement from 0mm to 20mm at speed of 0.1mm/sec. For case b) the model was exited in the direction of the pipe axis by harmonic waves of 0.7 Hz to 5.0 Hz varying the amplitude from 0.1mm to 4.0mm. For the above two cases, the earthpressure acting on the crown of the pipe was varied from $0.02kg/cm^2$ to $0.6kg/cm^2$.

Results of Static Test; Fig.2 shows the relationship between the static restoring force which is measured as a resultant force in the axial direction, and the displacement of the pipe for different earthpressures. From these curves, the apparent spring constant of the ground and the relative displacement when sliding occurs are estimated. By representing the friction force per unit length as F (kg/cm) and the external diameter as d (cm), the average frictional stress can be expressed as F/¶d and frictional coefficient s becomes,

$$s=F/p¶d \quad \text{------------------------------------} (1)$$

The frictional coefficients obtained Eq.(1) are plotted in Fig.3, where the values found by Kitade[3], Sakurai[4], and Miyamoto[5] are plotted together for comparison. 0.15-0.6 are considered to be the frictional coefficients at the initiation of sliding. Fig.4 shows the proportionarity relationship between the axial strain in the pipe and the restoring force. The axial strain is independent of the earthpressure. Assuming that the axial strain is caused by frictional force, the axial strain becomes as follows;

$$\varepsilon_A=¶dlC_0/AE \quad \text{-------------------------------} (2)$$

where l, A, C_0 and E represent the length of pipe, cross-sectional area, frictional force per unit area and Young's modulous, respectively. From Eq.(2), the frictional force F_T can be expressed in terms of the axial strain in the pipe, namely,

$$F_T=AE*\varepsilon_A \quad \text{-----------------------------------} (3)$$

In this experiment, AE equals $3.52*10^6$ kg and Eq.(3) is plotted as the dotted line. The experimental results are found to be distributed about the line given by Eq.(3). This shows that the estimation of the axial strain using Eq.(2) is satisfactory.

Results of Dynamic Test; Fig.5 shows the restoring force vs. frequency curves for different input displacements. In terms of frequency, these restoring forces are seen to be constant, so that the resonant state is not shown. The relationship between axial strain and restoring force is shown in Fig.6. In this figure, the relationship for the static case is also plotted for comparison with the dynamic case. As mentioned in the static case, these two quantities are proportional. The restoring force per micron of the pipe for static case becomes $4.0*10^6$ kg and for dynamic case, $2.7*10^6$ kg, that is, the restoring force per micron for dynamic case is 30% smaller than that for static case. Hence, from other reports[5] added to these experimental results, the next relation would be developed,

$$C_0' = (0.7 \sim 0.8) * C_0 \qquad (4)$$

where C_0 is the dynamic frictional force per unit area.

Fig.7 (a)-(d) show the hysteresis loops recorded by the oscillograph. It becomes clear from this figure that for low frequency regions, the curve is the softening type due to sliding, while for high frequency region curve indicates a hardening type at the point where the velocity changes sign. By examining the results for various tests it can be seen that for a given frequency the hysteresis loops for various displacement are the same shape and vary in size according to the displacement.

In Fig.8, the hysteresis loops are shown for the relative displacement. In this case, the earthpressure is $0.1 kg/cm^2$ and the frequency is 2 Hz. The thick line represents the maximum point curve. In Fig.9, the maximum point curves for different frequencies are shown. These curves are not affected by frequency, namely, the dynamic case can be treated as a static one. Maximum point curves of the frictional restoring force are approximately expressed in the form,

$$F_T = \frac{u}{|u|} k |u|^{\alpha} \qquad (5)$$

where u represents relative displacement and k and α are constants. By the method of least square, $\alpha=0.48$, $k=38$ and $\alpha=0.43$, $k=68$ are determined when earthpressure p is $0.02 kg/cm^2$ and $0.10 kg/cm^2$, respectively.

ESTIMATION OF RELATIVE DISPLACEMENT

Experimental results show that the effects of frequency on the nonlinear behaviour of the maximum restoring forces are not great, neglecting the hysteresis loops. For the sliding analysis of pipelines during earthquakes, the dynamic system could be considered as a static one. In the following analysis the form of $F=ku^{\alpha}$ is used as the relationship between the relative displacement and the restoring force.

For the interactive system between the pipe and ground, the equilibrium equation of motion in the axial direction is as follow;

$$EA \frac{\partial^2 u}{\partial x^2} - k's(U-u)^{\alpha} = 0 \qquad (6)$$

where u and U are displacement of pipe and ground respectively, and s, EA represent the circumference and the sectional rigidity of the pipe. When a seismic dilatational wave moves along the pipeline with phase velocity C_a, Eq.(6) can be rewritten using the relative displacement u^*,

$$EA \frac{\partial^2 u^*}{\partial x^2} + k's(u^*)^{\alpha} = -EA \frac{\partial}{\partial x}\left(\frac{V}{C_a}\right) \qquad (7)$$

V represents the velocity amplitude of the ground motion. Applying the relationship of

$$\frac{\partial}{\partial x}\left(\frac{\partial u}{\partial x}\right)^2 = 2\frac{\partial u}{\partial x} \cdot \frac{\partial^2 u}{\partial x^2} \qquad (8)$$

the strain amplitude of the pipe is calculated by the next equation.

$$\varepsilon_A = -\sqrt{\left(\frac{V}{C_a}\right)^2 - \frac{2k's}{EA}\frac{1}{1+\alpha}(u^*)^{1+\alpha}} \qquad (9)$$

If no relative displacement occurs in the system, u^* equals zero and ε_A equals $-V/C_a$, which is the well known equation for the estimation of the strain amplitude in ground under the influence of seismic waves. Eq.(9) gives the relationship among seismic disturbance, relative displacement and strain amplitude of the pipe. If we want to find the maximum strain level less than ε_s, the following relationship in terms of u_s^* is indispensable,

$$u_s^* \geq \left[\frac{EA(1+\alpha)}{2k's} \{ (\frac{V}{C_a})^2 - \varepsilon_s^2 \} \right]^{1/(1+\alpha)} \quad \text{------------} (10)$$

Eq.(10) implies that sliding displacement of the pipe must be larger than u_s^* when axial strain amplitude of the pipe is smaller than ε_s. The segment length l_s, in which sliding takes place is calculated as follows;

$$l_s = u_s^* / (\frac{V}{C_a} + \varepsilon_s) \quad \text{------------------} (11)$$

Fig.10 shows an example of the numerical calculation of Eqs.(10),(11). In this case, the outer radius and thickness of the steel pipe is 600mm and 9.5mm respectively and α is 0.04 and k' which is the value of k per unit area equals 0.03. In Fig.10, the relationship between acceleration and velocity was formerly given by the author et al by integrating 60 strong motion acceleration records. This relationship is shown in the next formulae,

$$\begin{aligned} T > 0.7;\ & V=0.2*A \\ 0.7 > T > 0.3;\ & V=0.1*A \quad \text{------------------} (12) \\ T < 0.3;\ & V=0.05*A \quad (T;sec,\ V;kine,\ A;gal) \end{aligned}$$

where T denotes the predominant period of the acceleration seismogram. From Fig.10, we know that effects of phase velocity C_a on the estimation of relative displacement are very large. Fig.11 shows the effects of α and k' on relative displacement. The smaller the values of α and k' are, the greater the relative displacement is. This tendency corresponds to the decrease of restoring forces with the decrease of α and k'.

CONCLUSION

Underground pipelines are generally connected to structures such as manholes,buildings etc which have large masses and act in the same way as the surrounding ground during earthquakes. The occurrence of relative displacement between pipe and ground during earthquakes would induce the concentration of stress or strain at the connected points above mentioned.

Flexible joints in pipelines which absorb the relative displacement u_s^* in the section length l_s are necessary to assure earthquake resistance by harmonizing the pipeline to the behaviour of the surrounding ground.

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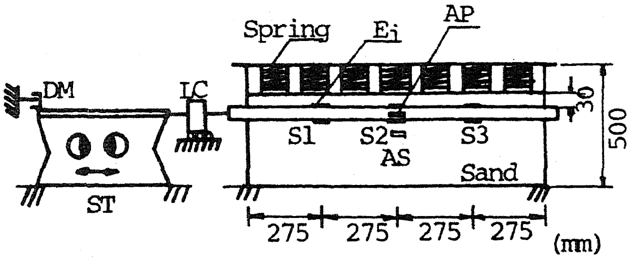

DM:Displacement meter
LC:Load Cell
Si:Strain Gauge(i=1-3)
AS:Accelero-meter of sand
AP:Accelero-meter of pipe
Ei:Earthpressure Cell(i=1-3)
ST:Shaking Table

Fig.1 Experimental device

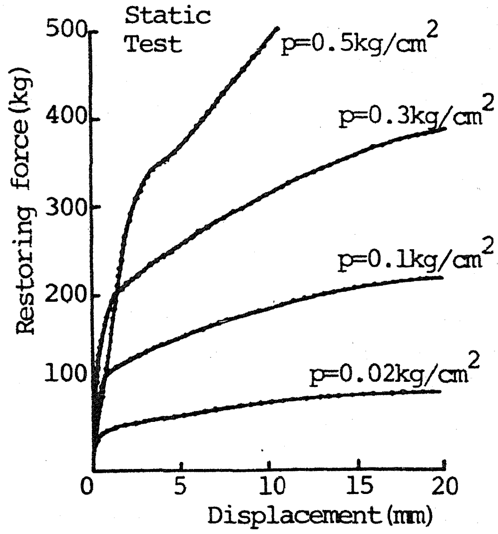

Fig.2 Relationship between restoring force and displacement

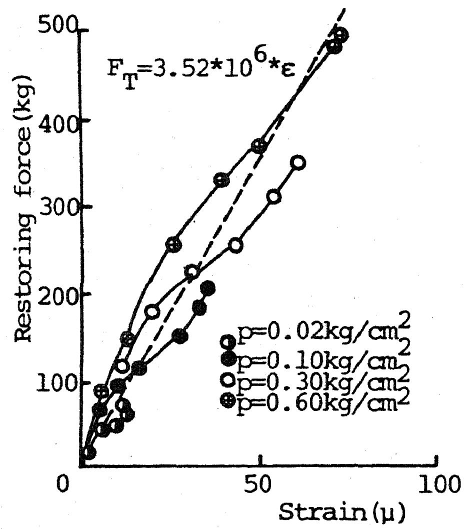

Fig.4 Relationship between restoring force and strain

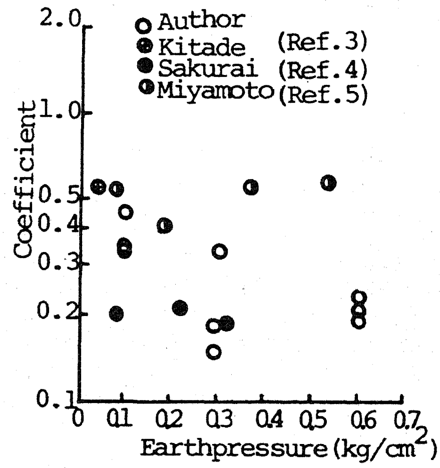

Fig.3 Coefficient of friction

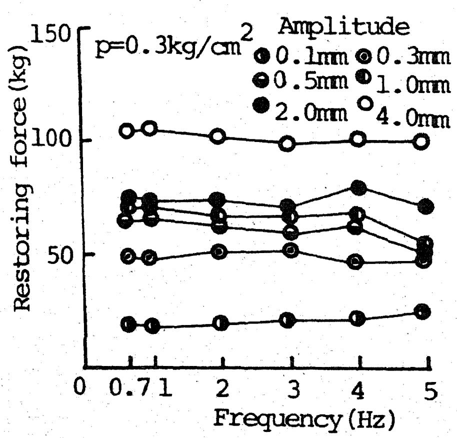

Fig.5 Frequency response of restoring force

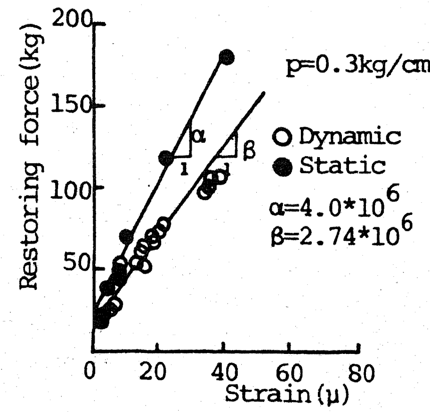

Fig.6 Relationship between restoring force and axial strain(dynamic test)

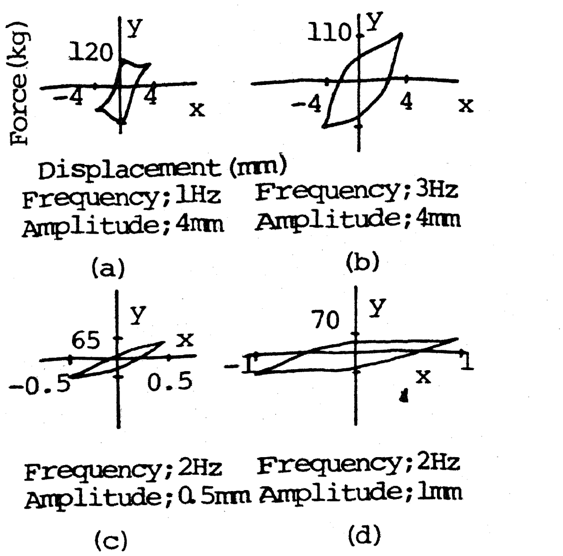

Fig.7 Hysteresis curves of restoring force.

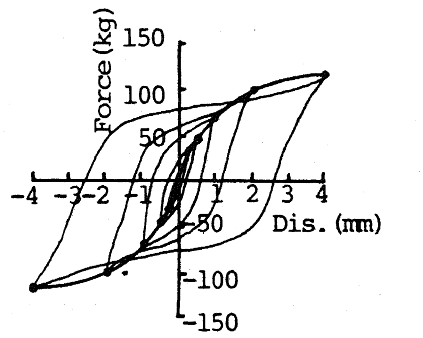

Fig.8 Hysteresis curves and maximum point curves of restoring force

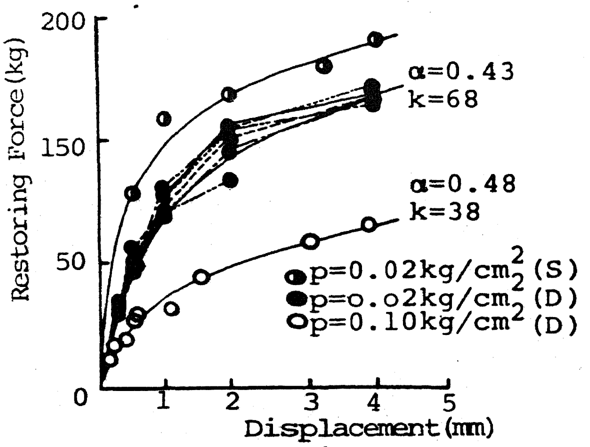

Fig.9 Maximum point curves

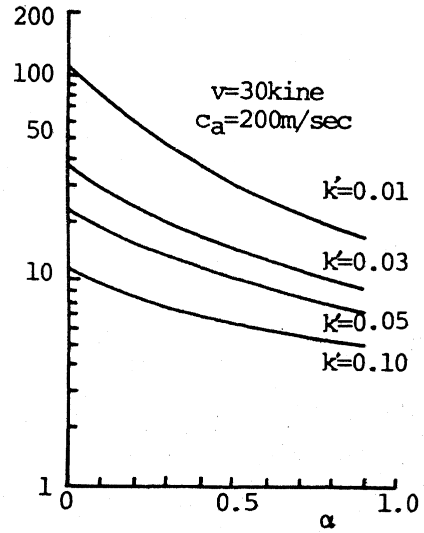

Fig.11 Effects of α, k' on relative displacement

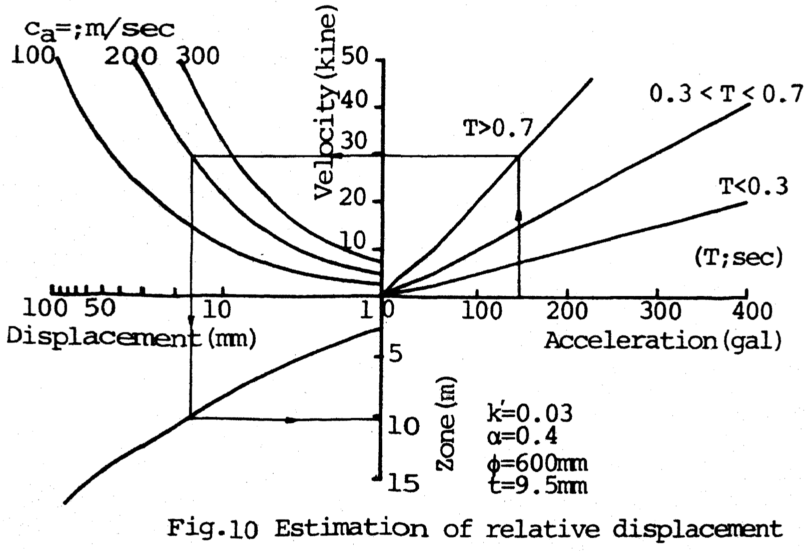

Fig.10 Estimation of relative displacement