SEISMIC BEHAVIOR OF BURIED PIPELINES THROUGH FIELD OBSERVATION

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This paper presents seismic response characteristics of embedded pipes based on field measurements. Strains induced in steel pipe and ductile pipes with expansion joints are studied. Special attention is placed for effect of bends on pipe response. Soil springs which are important in seismic design by means of the seismic deformation method is also studied based on the measured data.

Key Words: seismic deformation method, buried pipe, seismic design, strong motion observation

1. INTRODUCTION

Seismic design of embedded pipes is generally made by the seismic deformation method (4) in which embedded pipes are assumed to respond in accordance with strain induced in ground during earthquakes. Pipes are considered to be beams elastically supported by soils when the stiffness of the soil is modelled by springs. Although the seismic deformation method has been adopted for seismic design of embedded lifeline facilities, measured data available for evaluation pipe response during earthquakes is very limited. Strong motion observation was initiated for measuring pipe response, because precise evaluating of pipe response in ground is essential for improving seismic design method. Special attention was paid to obtain response data for pipe with bends and expansion joints.

This paper presents an analysis of the measured data of pipe response, and soil spring stiffness to be used in the seismic deformation method is also presented.

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2. OBSERVATION SYSTEMS

Fig. 1 shows the observation systems placed at Sodegaura city, about 50 km east of Tokyo, for measuring seismic behavior of embedded pipes. Continuous steel pipe with a diameter of 15 cm and ductile pipes with diameters of 15 cm (right side in **Fig.1**) and 30 cm (left side in **Fig.1**) are embedded 1 m below the ground surface As shown in **Photos 1 and 2**. The length of the continuous steel pipe is 120 m and there is a bend at 20 m from the right end. The length of one element of the ductile pipe is 5 m in the 15 cm diameter pipe and 6 m in the 30 cm diameter pipe. They were jointed together by expansion joints which are capable of absorbing a relative deformation of ± 10 % of pipe

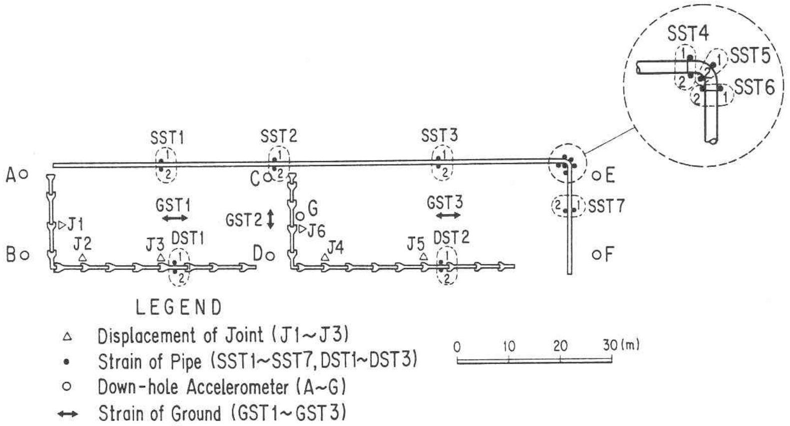


Fig. 1 Observation Systems

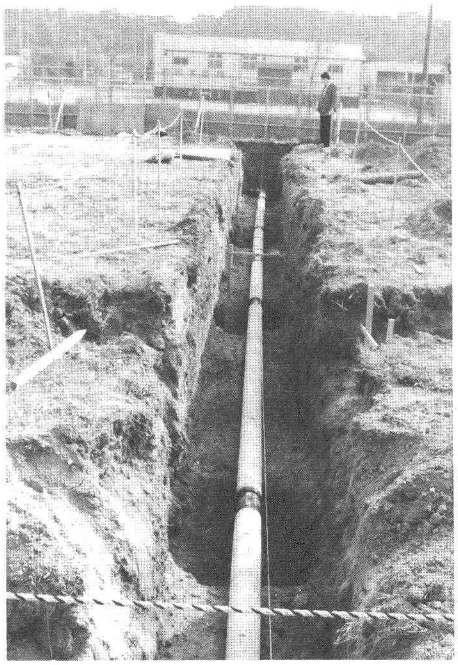


Photo 1 Steel Continuous Pipe (Straight Section)

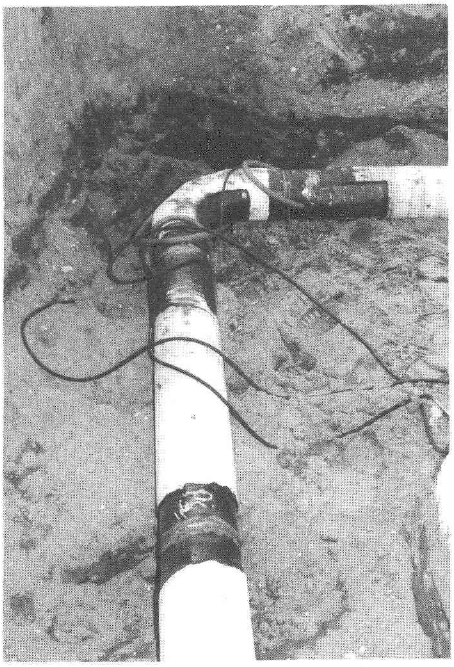


Photo 2 Steel Continuous Pipe (Bend Section)

length in the axial direction and a rotation of ± 6 degrees. Stoppers for preventing excessive pulling−out are provided at the expansion joints.

Dense instrumentation is made to measure the pipe response. The strain induced in the steel and ductile pipes as well as relative displacements developed between two adjacent ductile pipe sections were measured. Strain gauges with coating against water are placed on the both sides of the pipes so that the flexural strain as well as the axial strain could be detected.

The ground acceleration and ground strain were measured. Three−components down−hole accelerometers were installed at seven points to measure ground acceleration. The accelerometers A−F were installed 1 m below the ground surface, and the accelerometer G was installed 30 m below the ground surface. The measured data was used to compute the averaged ground strain induced at the site. Special devices were installed 1 m below the ground surface to directly measure ground strain. The devices consist of two 80 cm diameter circular plates and a 6 cm diameter double tubed steel rod. The circular plates were connected to the double tubed steel rod.

Movement of the circular steel plates in accordance with soils vibration during earthquakes would develop small relative displacements between the two circular plates. Ground strain may be evaluated by dividing the relative displacement by the length of the double tubed steel rod. This device has been successfully used for measuring ground strain at several observation sites 1) 3) .

All the measured signals are digitized with an interval of 1/100 second and recorded with a

Table 1 Major Earthquakes Triggered

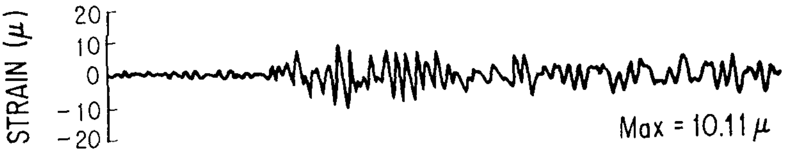
NO. OF EQ.	DATE	EPICENTER			MAGNITUDE (M)	FOCAL DEPTH (km)
		EPICENTRAL REGION	LONGITUDE	LATITUDE		
EQ−1	1989. 10. 14	NEAR IZU−OHSHIMA	135° 03′	34° 54′	5.7	25
EQ−2	1990. 6. 1	EAST OF CHIBA−KEN	140° 40′	35° 38′	6.0	70
EQ−3	1990. 6. 5	MIDDLE OF KANAGAWA−KEN	139° 20′	35° 50′	5.3	120
EQ−4	1990. 6. 27	SAGAMI−BAY	139° 07′	35° 00′	5.4	148
EQ−5	1990. 8. 23	MIDDLE OF CHIBA−KEN	140° 24′	35° 21′	5.4	50
EQ−6	1990. 8. 23	MIDDLE OF CHIBA−KEN	140° 24′	35° 21′	5.2	49
EQ−7	1990. 12. 11	MIDDLE OF CHIBA−KEN	140° 19′	35° 19′	4.0	35
EQ−8	1990. 12. 16	MIDDLE OF CHIBA−KEN	140° 13′	35° 37′	4.6	77
EQ−9	1991. 6. 28	TOKYO−BAY	139° 52′	35° 29′	4.6	68
EQ−10	1991. 7. 14	EAST OF NAGANO−KEN	138° 31′	36° 25′	5.4	187
EQ−11	1991. 9. 29	NORTH OF CHIBA−KEN	140° 06′	35° 45′	4.9	80
EQ−12	1991. 11. 19	TOKYO−BAY	140° 02′	35° 36′	4.9	81
EQ−13	1992. 2. 2	TOKYO−BAY	139° 08′	35° 20′	5.7	90

digital acquisition systems. Pre−event memory of about 10 seconds are provided to get full records from their start.

3. MEASURED DATA

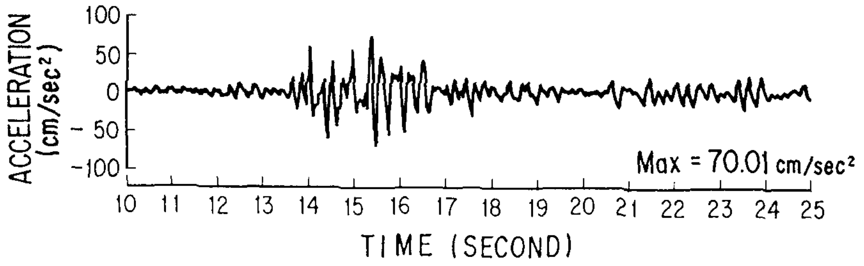
Observation was initiated in January 1989 and many records have been already obtained. In this report the pipe response was analyzed based on the measured data obtained after October 1989. Record which are large enough for analysis were measured by thirteen earthquakes as shown in **Table 1.**

(a) Strain at point SST1



(b) Strain at point SST2

(c) Strain at point SST3

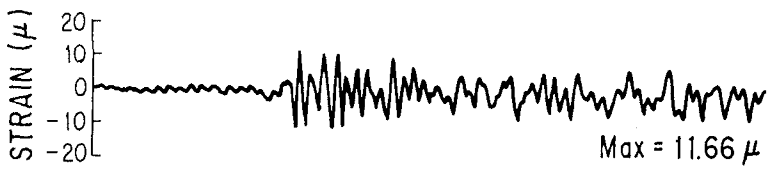


(d) Acceleration at point C

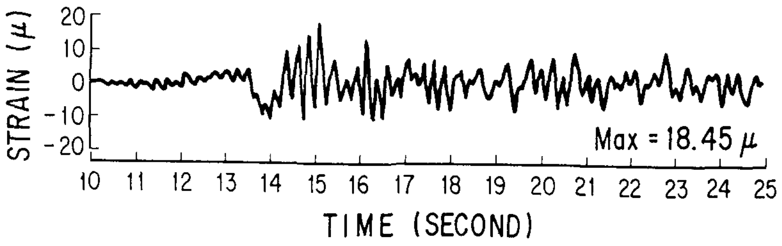
Fig. 2 Measured Axial Strain of Steel Pipe and Ground Acceleration C Point during EQ 13

Fig. 2 shows the measured axial strain induced in the steel pipe and ground accelerations developed by an earthquake with epicentral distance of 75 km and an earthquake magnitude of 5.7. This earthquake is designated hereinafter as EQ 13 earthquake. The peak ground acceleration was about 65 to 70 cm/sec ^{2} and the peak pipe strain was about 7.2 to 10.1 μ . It is interesting to note in **Fig. 2** that although there are many similarities of the pipe strains in the wave form between the three locations, they are not identical. This clearly shows that the pipe response in axial direction depends considerably on the response of nearby soil.

Because the ground motion was small, the devices for measuring ground strain did not directly detect ground strain. **Fig. 3** shows ground strains computed for the EQ 13 earthquake from measured

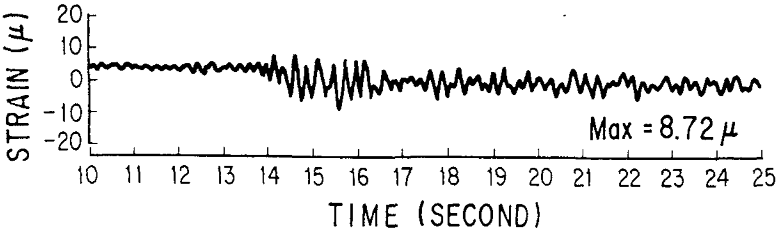


(a) Averaged Strain Between △ ABC

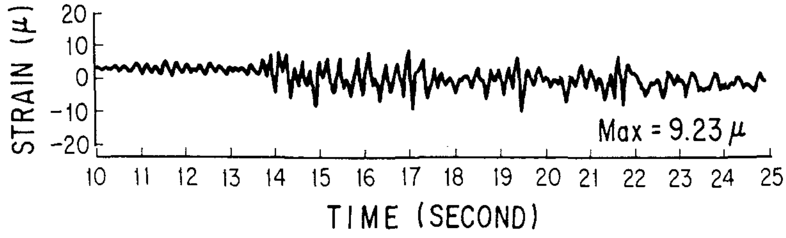


(b) Averaged Strain Between △ BCD

Fig. 3 Ground Strain Computed for EQ 13 from Measured Ground Acceleration



(a) Ductile Pipe with 30cm Diameter



(b) Ductile Pipe with 15cm Diameter

Fig. 4 Measured Axial Strain of Ductile Pipe during EQ 13 ground accelerations. The measured ground accelerations were double integrated to obtain the ground displacements (7). Assuming triangular elements such as Δ ABC and Δ BCD, the ground strain along pipe axis was computed with use of the standard finite element method (5). Linear interpolation function for displacements was assumed in each finite element. It should be noted in **Fig. 3** that there is some drift of zero strain at 13−14 second. Because the ground accelerations are quite small, there way be some error in computing the ground strain. It should be also noted that the peak strain is 1.6 times larger in Δ BCD than Δ ABC. This way be developed due to special variation of ground. If the ground strain computed for Δ ABC, which is the averaged ground strain between points A and C, is compared with the axial pipe strain at point SST1, in **Fig. 2**, it is found that the strains obtained are quite similar.

Fig. 4 shows axial strain induced during the EQ 13 earthquake in the ductile pipes. Almost no relative displacement was developed at the joints. It is interesting to note that the strain of the ductile pipe at the point DST−1 is quite similar with the strain of the steel pipe at the point SST−1. The strain of the ductile pipe is not necessarily smaller than the strain of the steel pipe. This implies that reduction of axial force induced in the ductile pipe due to the expansion joints was quite small during the EQ 13. The forces developed at the expansion joints during the EQ 13 were so small that friction at the expansion joints prevented slippage to occur between the adjacent pipe sections.

Fig. 5 shows a distribution of peak strain along the steel pipe for the EQ 13 earthquake. Both axial and flexural strains are presented. It should be noted that although axial strain is predominant in the straight section, flexural strain becomes larger than the axial strain at the bends. Flexural strain has to be therefore taken into account in seismic design of pipes at bend sections.

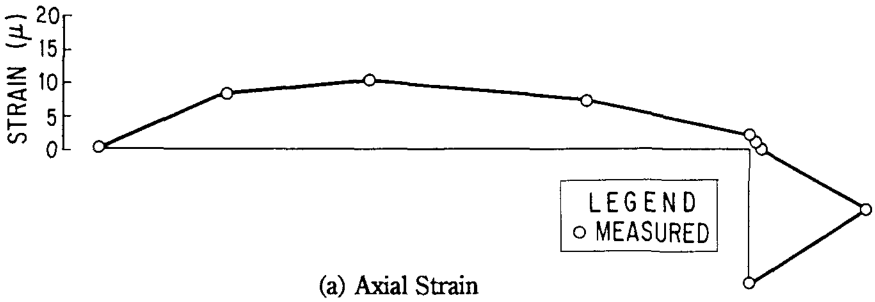
Fig. 6 shows the axial strain of steel pipe vs. peak ground acceleration in pipe axis relation for the data obtained by the thirteen earthquakes presented in **Table 1**. The strain at SST3 was plotted. Although number of the data obtained is still small, clear correlation between the pipe strain and the peak ground acceleration is observed. By increasing the number of data, this is expected to provide a practical estimation for the pipe strain induced during earthquakes.

4. EVALUATION OF SOIL SPRING STIFFNESS

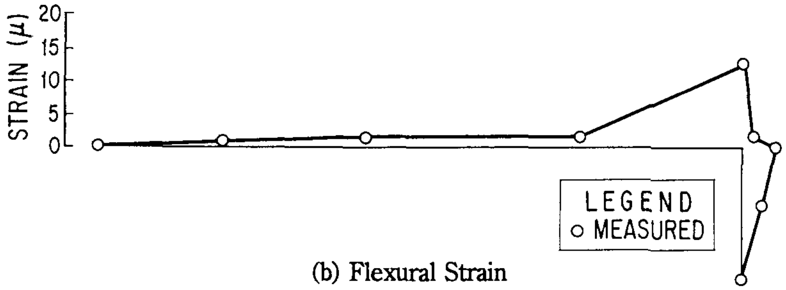
An analytical model presented in **Fig. 7** is often adopted to estimate dynamic response analysis of embedded pipes (6). The pipe is idealized by a beam elastically supported by springs which represent pipe −soil interaction. Soil response is computed by prescribing the input ground motion at the base rock.

In the analytical model presented in **Fig. 7**, it is essential to determine the stiffness of the soil springs which elastically support correctly the pipe. Various methods have been proposed from analytical and experimental studies to estimate the soil springs. However due to limitation of measured data available for estimating soil springs based on measured seismic response data of pipes, few studies have been made for soil springs. Therefore, with use of the analytical model presented in **Fig. 7**, the soil springs stiffness were studied.

The response displacements of soils which were estimated from the measured accelerations were used for computing the pipe responses. The steel pipe was idealized by a discrete analytical model with 24 beam elements as shown in **Fig. 8**. Because the displacements which were computed



(a) Axial Strain



(b) Flexural Strain

Fig. 5 Peak Strain of Steel Pipe during EQ 13

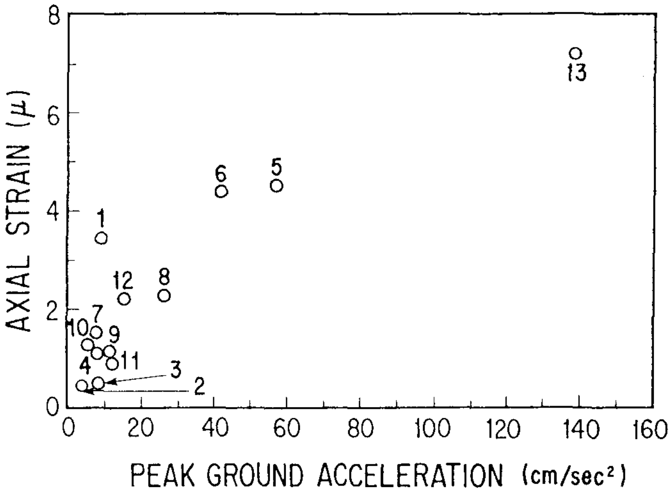


Fig. 6 Axial Strain of Steel Pipe vs. Peak Ground Acceleration Relation

from the measured accelerations were available at only six points, the displacements at each nodal point of the analytical model were computed from either linear interpolation or extrapolation of the displacements from the six points.

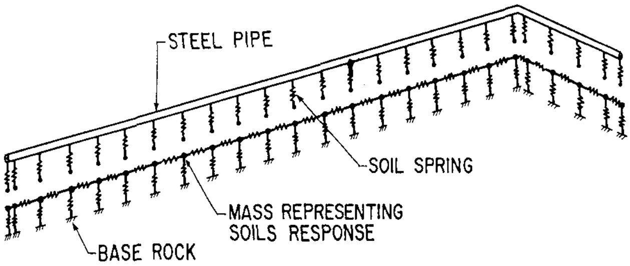


Fig. 7 Analytical Model for Dynamic Response Analysis of Embedded Pipes

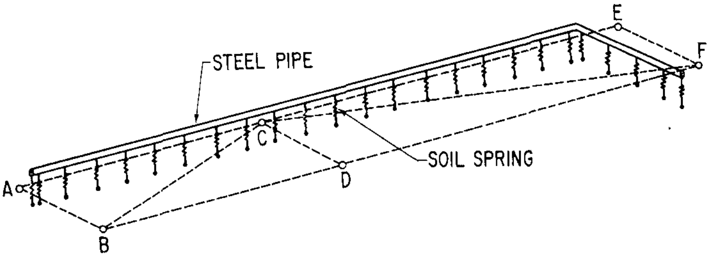


Fig. 8 Analytical Model Used for Pipe Response

In the Design Specifications of Petroleum Pipelines [2)] , the soil spring stiffness is stipulated to be estimated as

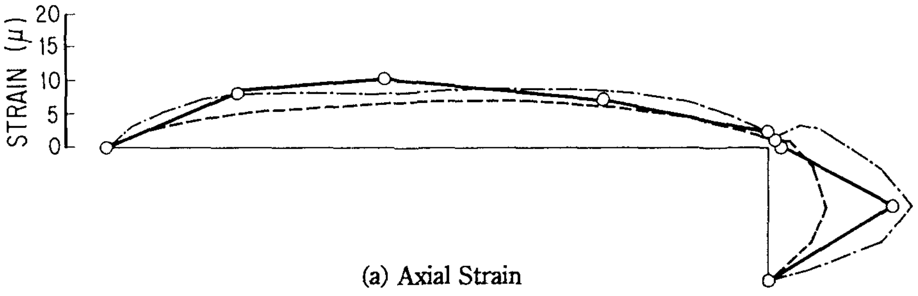
$$K = c \times G_s \qquad (1)$$

where K : stiffness of soil spring per unit length, c : a coefficient, and G_s : shear moduli of soils. The shear moduli of soils are estimated as

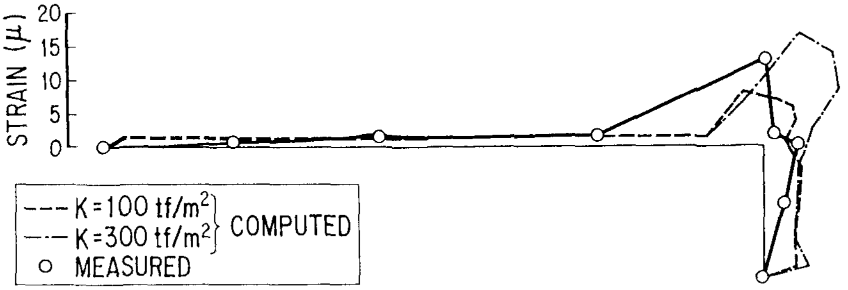
$$G_s = \frac{\gamma_t}{g} \times V_s^2 \qquad (2)$$

where γ_t : unit weight of soils, V_s : shear wave velocity of soils, and g : acceleration of gravity. In the specifications the coefficient c is stipulated to be determined by appropriate tests, and a value of 3.0 is recommended when such test data is not available.

The soil spring which gives realistic estimation for the measured pipe strain was therefore studied. **Fig. 9** shows the approximation of the computed pipe strain assuming a soil spring stiffness of 100 tf/m ^{2} and 300 tf/m ^{2}. The computed axial and flexural strain along the longer straight pipe approximates quite well the measured pipe strain. However the approximation along the shorter straight pipe and bent is rather poor. Approximation at these parts require further clarification by accumulating the measured data. Because shear wave velocity which was measured at three points in the observation site was about 150 m/sec at the depth between the ground surface and 15 meters below the ground surface, the soil spring stiffness of 100tf/m ^{2} and 300tf/m ^{2} are predicted by assuming a coefficient "c" of about 0.05 and 0.16 respectively in Eq.(1). From such evidence it may be said that the recommended value of 3.0 for the coefficient "c" in Eq.(1) is excessively conservative. It is important to precisely study the coefficient "c" which gives a realistic soil spring stiffness.



(a) Axial Strain



(b) Flexural Strain

Fig. 9 Best Correlation of Pipe Strain for EQ 13

5. CONCLUSIONS

For accumulating actual seismic behavior of embedded pipes during earthquakes, seismic observation of two types of pipes was initiated. Based on the analyses of the measured data on the strain of embedded pipes, the following conclusions may be deduced:

1) Although axial strain is predominant in the straight section, flexural strain is more predominant than axial strain at the bend section of the pipe based on the measured data. Flexural strain should be considered in seismic design at bend sections.

2) Considerably good correlation was observed between the measured axial strain of the pipe and the peak ground acceleration. Accumulation of measured data is expected to provide a realistic estimation method for the pipe strain based on the peak ground acceleration.

3) The computed pipe strain assuming Eqs.(1) and (2) was excessively larger than the measured pipe strain. It is thought that the spring stiffness predicted by Eq.(1) assuming the coefficient "c" of 3.0 is too conservative. Coefficient "c" has to be precisely studied by analyzing more measured data.

6. FUTURE DIRECTIONS

Accumulation of measured data is required for providing a realistic estimation method for the pipe strain based on the peak ground acceleration, and for studying the coefficient "c" which gives a realistic soil spring stiffness. Because the observation site is located at one of the highest seismicity area in Japan, it is anticipated to have a number of measured data in a short time.

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