Dynamic Stresses of Underground Pipe Lines During Earthquakes

by

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Synopsis

The results on dynamic behaviours of underground pipe lines are presented, which were observed on three kinds of pipe lines during the Matsushiro Earthquakes. The observed stresses of pipes are discussed in connection with the observed deformations of ground, the wave character of ground and the phase of seismic waves.

The principal strain of ground are also calculated from the strain records which were observed by the new-designed earth-strain meters. The observed results are compared with the results of vibration tests and many kind of soundings, and an estimative process to the pipe stress are presented.

List of Symbols

a_0	amplitude of ground movement
A	acceleration of earthquake
A_0	sectional area of pipe
C_0	friction per unit pipe length
C	constant relating to pipe strain
D	diameter of pipe or tunnel
E	Young's modulus of pipe material
f	constraint of ground against pipe line
k	spring constant of surrounding ground
ℓ	a half length of seismic wave
L	length of seismic wave
p	circular frequency of ground movement; $= \frac{2\pi}{T}$
r_0	radius of pipe or tunnel
t	co-ordinate of time
T, T'	period of ground movement
u	relative displacement between pipe and ground

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u_0	yield point of ground's constraint
v	apparent velocity of seismic wave incident to pipe line
v_a	velocity of longitudinal wave propagating in pipe line; $= \sqrt{\frac{E}{\rho}}$
v_s	velocity of pure shear wave propagating along the surface if exist.
V	velocity of seismic wave
x	co-ordinate of distance
y	movement of pipe line
Y	movement of ground
$\varepsilon, \varepsilon_m, \varepsilon_m$	strain of pipe line or ground
λ	a distance between anchors
ρ	density of pipe material
ω_0	natural circular frequency of rigid pipe line; $= \sqrt{\frac{k}{\rho A}}$

1. Introduction

Dynamic behaviours of Underground pipe lines during earthquakes remain unknown, while the structures in weak ground have suffered damages from large earthquakes. From the aseismic point of view, the problems lie in the fact that the dynamic behaviours of the structures have little relations to ground acceleration, but to ground deformation, and in the fact that such structures have two dimensional extension along the surface of ground. As many investigations of the earthquake engineering treated ground acceleration such as the one at a point, they give little informations for ground deformation or distribution of ground displacement along the surface.

The Matsushiro Successive Earthquakes offered a lot of earthquakes and many chances to earthquake engineers in a brief period of time. The Earthquakes enabled us to research two or three dimensional properties of seismic wave propagation in ground, and to test dynamic responses of full sized models due to real earthquakes regarding a ground as a large shaking table.

In this paper a consideration on aseismic design of underground pipe lines is presented, based on the observed records of the wave propagative properties, ground strain, and pipe strain for three kinds of pipe lines during the Matsushiro Earthquakes.

2. On the Matsushiro Earthquakes

The Matsushiro Earthquakes occured at Aug. 3, 1965 and counted the number of earthquake frequencies up 653,908 untill March 31, 1967. The earthquakes are inactive, but do not end in present. The maximum magnitude was 5.3 in the past. The activity of earthquakes is shown in Fig. 2. 1 and Table 2. 1.

The focuses of earthquakes were beneath Mt. Minakami in the Matsushiro town, the Nagano province at first, and the region enlarged to the north-east and to the south-west. In Jan. 1967, the new focuses appeared beneath Mt. Kamuriki and Mt. Azumaya. The term of this researches contained the third period of strong activities in Aug. and Sep. 1966 and the forth in Jan. and Feb. 1967 (Fig. 2.2).

3. The Experiments

The test field was sited at the yard of Hokushin transformer station, the Chubu Electric Power Co. and is about 10 kilometres distant from Mt. Minakami in the west and about 11 kilometres from Mt.Kamuriki in the north.

The next items of observations during earthquakes were conducted in order to research the dynamic behaviours of pipe lines;

(1) The amplitude distribution of acceleration and properties of seismic wave propagation in the direction of depth.

(2) The amplitude distribution of displacement and properties of wave propagation along the surface of ground.

(3) The ground strain and properties of the principal strain and the principal angle near the surface.

(4) The dynamic behaviours and pipe strain for three kinds of pipe lines.

The followings were researched relating to the above observations;

(1) Boring Soundings to -50.0 metres.

(2) Standard penetration test and Sweeden penetration test.

(3) Elastic wave soundings and vibrator tests on properties of ground for surface waves.

(4) Micro-tremour measurements

(5) Vibrator tests for pipe lines

(6) Measurements on dynamic spring constant at the test ground.

The three proto-type models of pipe typed electric transmission lines for ultra high voltage (60 kV - 275 kV) were tested, and their dimensions were presented in Table 3. 1. The moving coil type seismographs were used without amplifier considering its stability in long test term. For the research on propagative properties of seismic wave in the direction of depth, a part of the seismographs placed in the ground, one set siting in -3.0 metres, -10.0 metres and -30.0 metres from the surface and other set in -5.0 metres and -10.7 metres at 50 metres distance from each other. Other seismographs distributed on the pipe lines and in the ground parallel with pipe lines in order to compare the difference of dynamic behaviours between pipe lines and ground.

The ground strain during earthquakes was observed by earth strain-meters which were newly designed by the authors used to the same principle of the seismograph. The 45 and 90 degrees rosette composed by three earth strainmeters was placed 0.4 metres under the ground for calculating the principal strain of ground.

In the Matsushiro Earthquakes, comparably large earthquakes appeared in a brief period of time. That was able to measure pipe line stress by usual method. The electric wire strainmeters and Carlson's strainmeters were used in the experiments. Usual number of measurements was counted up more than 120 points.

4. The Results

The number of earthquake records reached to several hundreds and pipe strain records were counted up to about one hundred. The earthquake 03:04, Oct. 26, 1966 was the maximum one experienced in the term of pipe strain measurements. The Magnitude was 5.3 and its maximum acceleration observed at the test field was 83 gal. Through the observed period of the project which contained this pipe line experiments, the maximum acceleration observed in the test field reached 196 gal in the earthquake 13:09, Aug. 28, 1966 of which magnitude was 5.3.

The observed records concerning the stresses of underground pipe lines showed that

(A) On the dynamic behaviours

(1) No difference of pipe lines and ground deformation was observed.

(2) On the ground deformation, the axial deformation was nearly equal to the transverse deformation.

(B) On the pipe strain

(1) At the straight part of pipe line, the axial strain was predominant.

(2) At the part of bend, the strain due to bending moment was observed. The strain of the bend did not large compared with the straight part.

(3) The maximum strain of pipe lines did not appear at the time when the acceleration of ground reached maximum. The maximum strain appeared at the after phase of seismic waves.

(4) The strain at the connecting part of pipes and man hole did not large compared with another part for 250A pipe, but large stress concentration was observed in the concrete pipe. The bending strain at the connection was predominant, but at brief distance from the part the axial strain became predominant. At the after phase of seismic waves the axial strain at the connection became predominant.

5. Considerations

In order to investigate pipe line stresses during earthquakes, the next problems should be decided: (1) Are there something to differ between pipe line and ground deformation? (2) Which of pipe stress predominate, bending stress or axial stress? (3) Which phase of seismic waves cause the maximum pipe stress?

On the problem (1), the observed records showed that the pipe line deformation was equal to the ground deformation, and the natural frequencies or the increase of amplitude of pipe deformation did not recognized. Let this problems inspect to further details. Suppose the ground movement as

$$Y(x,t) = a_0 \cdot \mathrm{Sin}\ p(t - x/v) \tag{5.1}$$

and f as constraint of ground

$$f = k' \cdot \frac{u}{u_0} \equiv k \cdot u \qquad (0 \leqq u \leqq u_0) \tag{5.2}$$

$$= C_0 \qquad (u_0 < u) \tag{5.2'}$$

where

$$u = Y - y$$

In the range of $u < u_0$, the vibrational equation of pipe lines in the axial direction (cf. Fig. 5. 1),

$$\rho A_0 \frac{\partial^2 y}{\partial t^2} - EA_0 \frac{\partial^2 y}{\partial x^2} + ky = k \cdot a_0\ \mathrm{Sin}\ p(t - x/v) \tag{5.3}$$

The solution of the eq. (5.3) is

$$y(x,t) = \frac{1}{1 + (\frac{p}{\omega_0})^2 (\frac{v_a}{v})^2 - (\frac{p}{\omega_0})^2} \cdot Y(x,t) \tag{5.4}$$

The impact test showed that ω_0 was about 100 C/S for 250A pipe without cable. If in the case of pipe with cables, $(p/\omega_0)^2$ may be negligible compared with unit. Then neglecting the inertia effect, the decrease of pipe line deformation compared with ground is shown in Fig. (5.2). The same situation was presented in the transverse vibration. The transverse vibration tests on 250A pipe showed that the dynamic spring constant surrounding pipe was larger than 30Kg/cm/cm, even though sand surrounding pipe became the state of lequifaction. The natural frequency of 250A pipe with cables was larger than 20 C/S. Considering the cycle range of seismic waves in weak ground and the damping due to surrounding ground, dynamic effects of transverse vibration for many pipe lines are negligible. Fig. 5.3 shows the decrease of pipe line deformation for transverse deformation.

The conclusion on the problem (1) is that the deformations of pipe lines used in the experiment can be regarded as the same of ground. In the comparabley large earthquakes, axial deformation is not equal to ground. This will be discussed latter.

Though the axial deformation of pipes was nearly equal to the transverse deformation, the axial strain of all pipe lines in all eathquakes was predominant. The fact was explained by the difference of stress sensitivity between axial and transverse deformation. Supposing ground deformation as eq. (5.1) and letting the same amplitude and the same wave length, the calculated ratio axial strain to bending strain of pipe lines is shown in Fig. (5.4). For example, the ratio for 250A pipe is about 30, supposing the seismic wave velocity v=100 m/sec period T=0.5 sec - or if ground strain is 30 x 10^{-6} strain, axial strain of pipe lines is 30 x 10^{-6} strain while bending strain is 1 x 10^{-6} strain. As the diameters of pipe lines become larger the ratio become smaller, then the bending strain should be supperposed for pipe lines such as subway tunnels (See Appendix).

The conclusive notes of the problem (1) and (2) above mentioned induce the relation for pipe line stresses during earthquakes as follows. As records of earthquakes abound with acceleration records, let obtain the relation between strain and acceleration. Supposing pipe line strain equal to ground strain and assuming ground deformation as eq. (5.1), axial strain of pipe line is given as

$$\varepsilon = -a_0 \cdot \frac{p}{v} \cos p(t - x/v) \qquad (5.5)$$

and acceleration of ground as

$$A = -a_0 \cdot p^2 \sin p(t - x/v) \qquad (5.6)$$

The maximum strain is

$$\varepsilon = \frac{a_0 \cdot p/v}{a_0 p^2} \cdot A = \frac{1}{2\pi} \cdot \frac{T \cdot A}{v} \qquad (5.7)$$

The relation (5.7) is supported by the observed records of pipe strain as shown in Fig. (5.5).

Following this relation (5.7), the strain concerns with not only acceleration and period or deformation velocity of ground (T·A), but also the apparent velocity v of seismic waves incident to pipe lines. Also the apparent velocity concerns with the kind of seismic waves and softness of ground. For example, if the seismic waves incident to pipe lines propagate with the normal to them, the apparent velocity v become infinity and no strain of pipe lines induce. The observed records of seismic waves in a direction of depth and along the surface showed that the phase of S wave - especially the first part of S waves - produce no strain of pipe lines layed parallel to the surface. This demonstrated by the fact that the strain of the pipe lines appeared at the time when the maximum acceleration had appeared already.

Do shearing waves propagate along the surface during earthquakes? If shearing waves appear, such a strain as follows will induce. Assuming such seismic wave as pure shear wave, the expansional wave is induced in a direction of 45 degrees to that direction of propagation and the amplitude of induced wave is one half to the original wave. Even in this case, the axial strain will observe in pipe lines, because the strain sensitivity above considered is much larger than 2. The strain induced by pure shear wave is given as

$$\varepsilon = \frac{1}{4\sqrt{2\pi}} \cdot \frac{T \cdot A}{v_s}$$

for the incidence of 45 degrees direction to pipe lines.

For the evaluation of pipe line stresses during earthquakes, it is most important which phase of seismic waves cause the maximum pipe stress. It was thought that the principal strain of ground would give good informations for the problem, so the observations of ground strain were conducted in this experiments.

An example of the principal strain calculated by the strain records in three directions is shown in Fig. 5.6. The some of the results was as follows:

(1) The principal strain of ground surface as same as pipe strain did not reach the maximum when acceleration or displacement of ground became maximum.

(2) The pure shear wave along the surface was not apparent, because the calculated waves of both principal strain were the same in phase.

(3) The variation of the principal angle with time duration have some

character at the boundary of P-wave, S-wave and after phase's wave in seismic waves. An example in Fig. 5.5 shows the sudden variation at the boundary of P-wave and S-wave. After the next variation which is not so sudden as at the P-S boundary, the surface wave become to appear which can be distinguished by the observed records of seismic waves under the ground.

Considering the results of ground strain in connection with results of experimental studies for elastic waves and on propagative character obtained by the observed seismic waves, the effective wave for aseismic design of underground pipe lines may not be S-wave but surface wave especialy in homogeneous ground.

As the strain of pipe lines concerns with the period of acceleration, the microtremour measurements were concucted and were compared with the periods of strain waves and seismic waves. The results of the measurements at the surface and in the ground gave good agreement with the one of earthquakes. The periods which were 0.10 sec, 0.25 sec and 0.36 sec at the surface correspond to the predominant periods of earthquakes which were 0.15 sec, 0.25 sec and 0.40 sec, while both periods differed slightly from point to point in the test yard. The period when the maximum acceleration appeared is uncertain, relating to the magnitude of earthquakes, the period of seismic activity and etc.. The periods, 0.15 sec and 0.25 sec, appeared mostly at the time when acceleration became maximum, while the predominant period of pipe line strain was 0.40 sec which coincided with the period obtained by the after phase of seismic records. Even though there was a certain case of which the predominant period in after phase was greater than 0.4 sec, it may be said that the predominant period obtained by microtremour offers good informations to the predominant period of pipe line stress.

6. Additional Consideration

The relation (5.7) is in the case of which relative displacement between pipe lines and surrounding ground is negligible. When earthquake becomes a certain extent, the relative displacement occurs in axial direction. The extent is given as follows:

$$u = Y - y \geqq u_0 \qquad (6.1)$$

or

$$\frac{AT^2}{4\pi^2} = u_0 \left\{ 1 + \frac{1}{(\frac{p}{\omega_0})^2 \ (\frac{V_a}{V})^2} \right\} \qquad (6.2)$$

$$\fallingdotseq u_0 \qquad (6.2')$$

Of course, we assume the wave length of earthquake is contained in extent of pipe lines. By quasi-dynamic test on 250 A pipe placed 1.5 metre beneath the surface, and surrounded by sand, u_0 was less than one milimetre. Assuming the relative displacement attain to the extent at large earthquake and uniform frictional force occurs all over pipe line, the upper bound of strain for straight pipe line is

$$\varepsilon_u = \frac{C_0 \cdot L}{4EA_0} = \frac{C_0 \cdot vT}{4EA_0} \qquad (6.3)$$

During large earthquakes, the movement of man hole, bend and branch contained in pipe line can be regarded as the same as ground movement.

We denote λ as a distance between man hole and branch or so on. When the relative displacement occurs all over pipe line, the mean strain of pipe line in the distance λ is

$$\varepsilon_m = \frac{a_0}{\lambda}\left[\operatorname{Sin} p\left(t-\frac{T}{4}\right) - \operatorname{Sin} p\left\{t-\frac{T}{4}\left(1+\frac{4\lambda}{L}\right)\right\}\right] \qquad (6.4)$$

The maximum ε_m with time duration is

$$\varepsilon_m = \frac{1}{2\pi}\cdot\frac{L}{2\lambda}\cdot\frac{AT}{v}\left[1-\operatorname{Sin}\frac{2\pi}{4}\left(1+\frac{4\lambda}{L}\right)\right] \qquad (6.5)$$

When $2\lambda = v\cdot T'$ or $2\lambda = L$,

$$\varepsilon'_m = \frac{1}{\pi^2}\cdot\frac{AT'}{v} \qquad (6.6)$$

Fig. 4.1 and Fig. 4.2 show comparably large strain of pipe lines at the phase of S-waves. This strain was induced by the non-homogenity of the test field. Fig. 6.1 is a record of ground displacement which was observed by the seismographs distributed on the surface and placed each other apart 30 metres in axial direction. Fig. 6.2 shows the seismic displacement in 30 metres underground which was calculated from the record shown in Fig. 6.1 by the elastic wave theory [1]. The calculated waves at S phase resemble each other although the observed record at the surface comparably differ each other. The mean strain of ground calculated from the observed displacement shown in Fig. 6.1 is presented in Fig. 6.3. It is comparably large compared with at after phase.

7. Conclusion

The above considerations enable us to evaluate dynamic stresses of underground pipe lines during earthquakes.

(1) The axial strain of pipe line become predominant and is presented by the next relation,

$$\varepsilon = C\cdot\frac{TA}{V} \qquad (7.1)$$

Following this, the strain concerns with

- (a) the phase of seismic waves (C,V)
- (b) the softness of ground (V)
- (c) the deformation velocity of ground (T·A).

(2) The process to evaluate the stress are as follows:

- (a) To measure the velocity of elastic waves in the ground of which construction of pipe lines is planed.
- (b) To decide the deformation velocity of the ground. For the aseismic design, acceleration for pipe line need not to adopt the same value for structures constructed on the surface of ground.

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[1] E. Shima "Modifications of Seismic Waves in Superficial Soil Layers as Verified by Comparative Observations on and beneath the Surface" Bull. of Earth. Res. Inst. Vol 40, 1962

(3) The after phase of seismic waves or surface waves may induce large stresses for pipe lines in homogeneous ground, but it is noted that the comparably large stresses will appear in non-homogeneous ground at the S-phase.

Fig. 7.1 shows the relation (7.1) assuming $C=1/2\pi$. By Fig. 7.1, the strain become large when V is less than 300 m/sec. In generaly, the velocity of effective seismic waves is less than 150 m/sec in weak ground, then large strain in weak ground will occur during large earthquakes. For example, assuming that $V = 140$ m/sec, $T = 1.35$ sec and $A = 100$ gal, the strain become about $1{,}500 \times 10^{-6}$ strain. This, ground strain, may explain some of cracks which occur in weak ground during large earthquakes.

8. Acknowlegement

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Appendix

For pipe lines with large diameter, the bending stress must be superposed to the aixial stress. Assuming the ground movement as $Y = a_0 \cdot \sin p(t - x/v)$, the bending strain of pipe is given as the next relation.

$$\varepsilon = \frac{r_0}{V^2} \cdot A$$

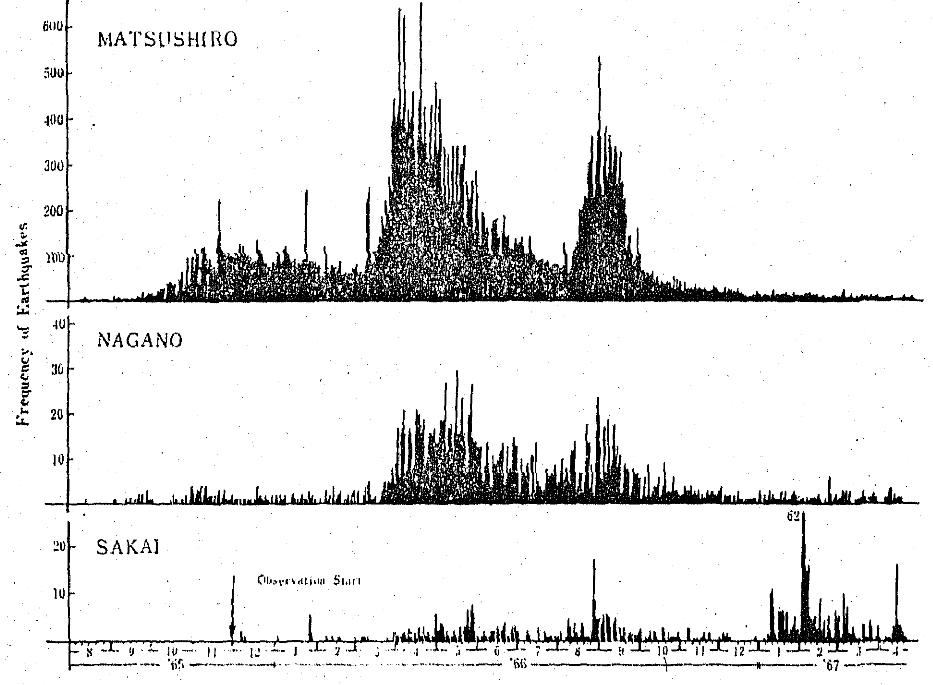

Fig. 2.1 Histogram of MATSUSHIRO Earthquake's

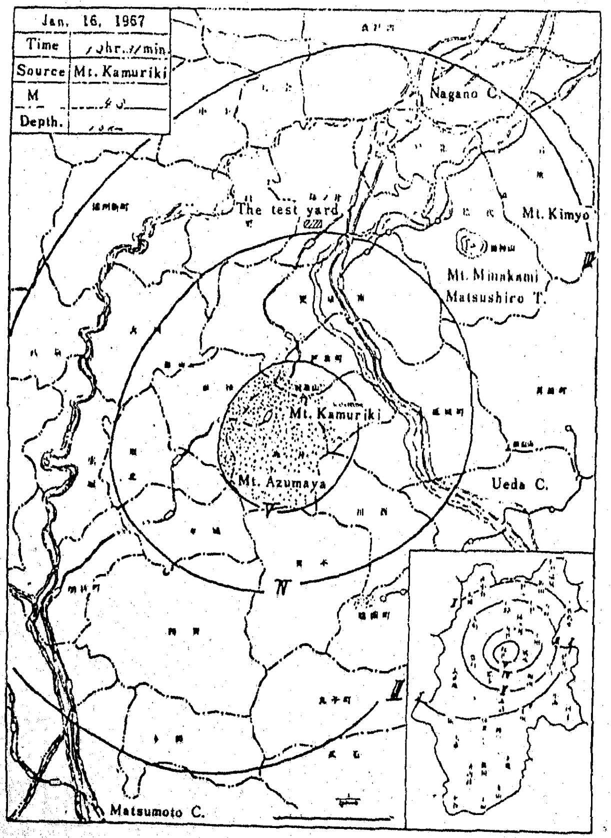

Fig. 2.2
A epicentre of
earthquake

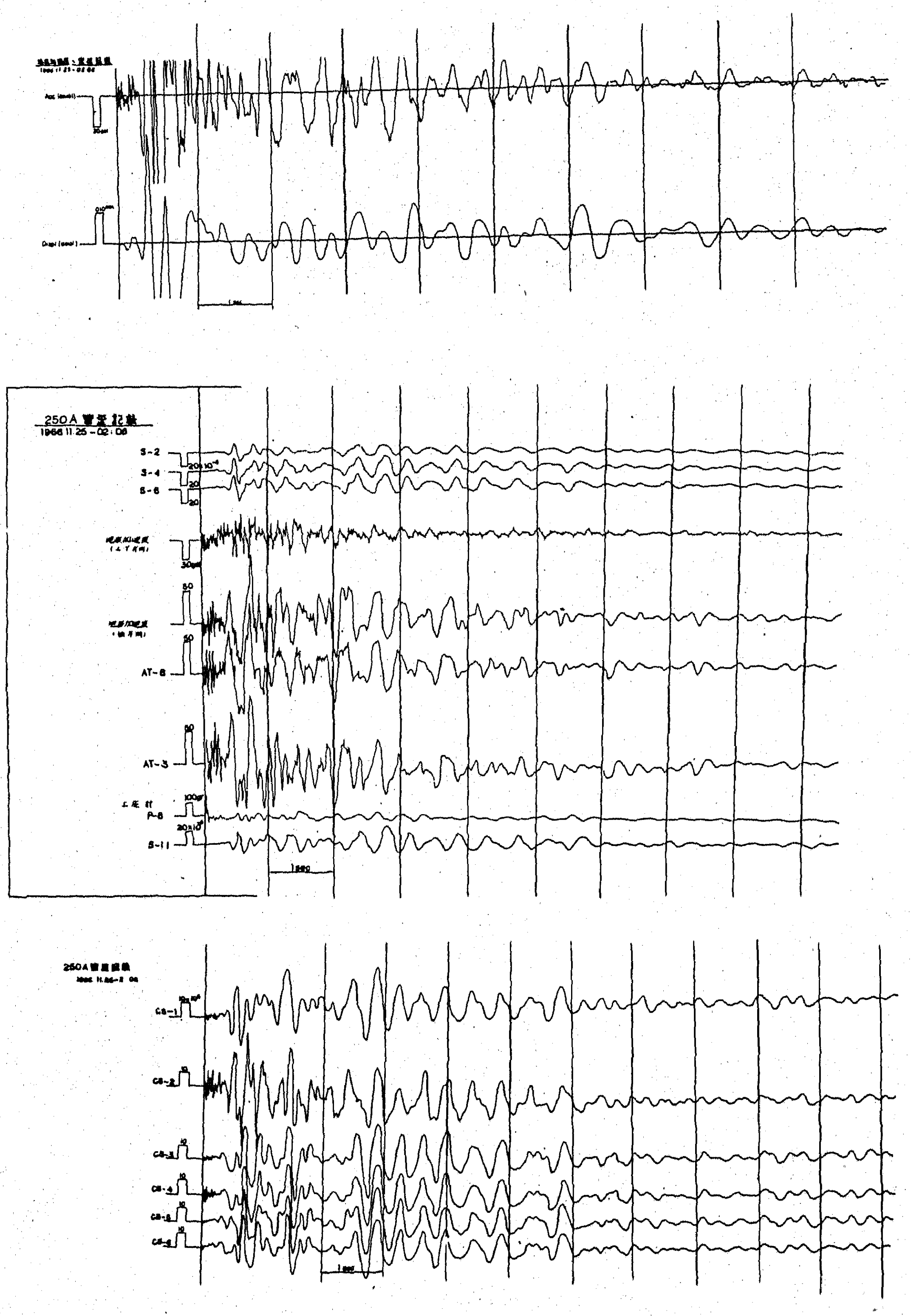

Fig. 4.1 The records of acceleration, displacement and strain of 250A pipe

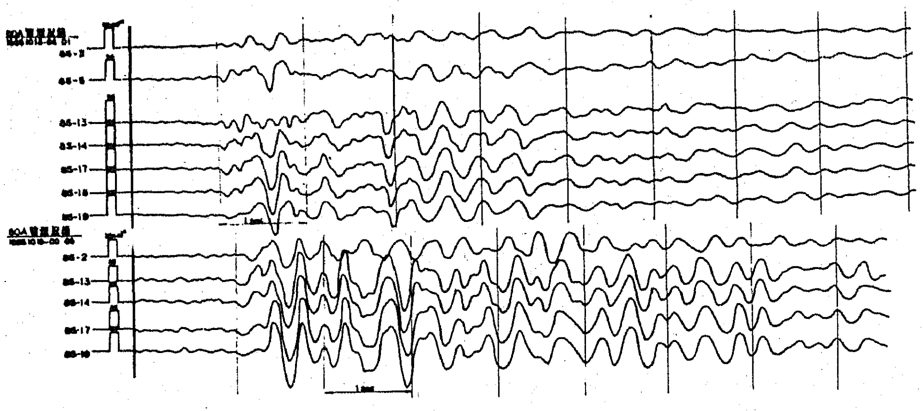

Fig. 4.2 The strain records of 80A pipe

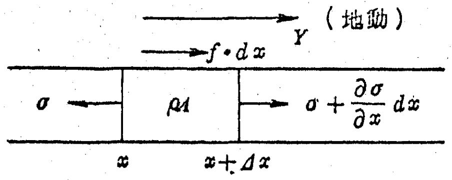

Fig. 5.1

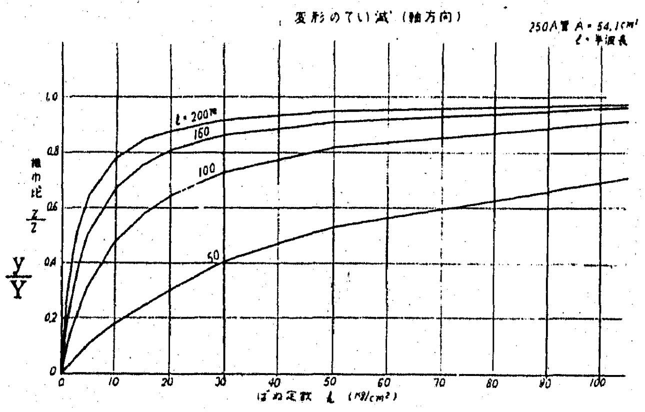

Fig. 5.2
The decrease of pipe's axial deformation due to ground elasticity

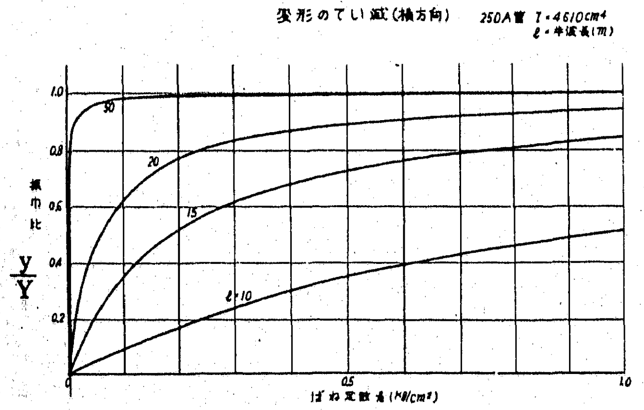

Fig. 5.3
The decrease of pipe's transverse deformation due to ground elasticity

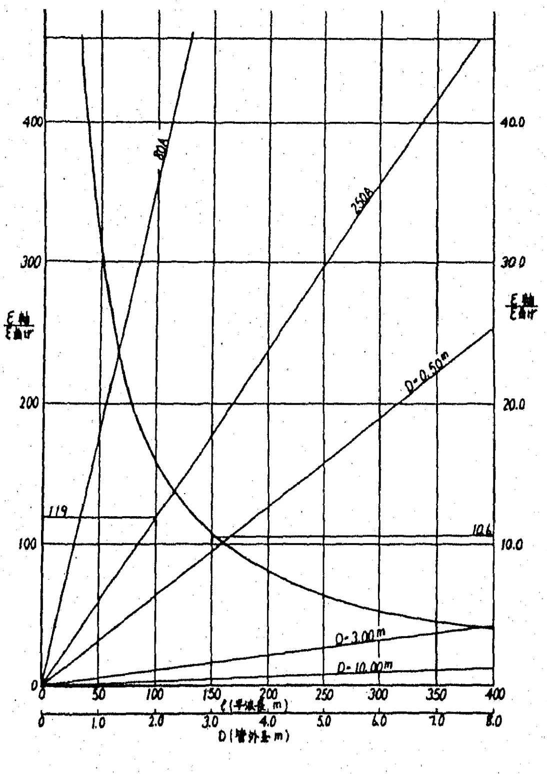

Fig. 5.4 The stress sensitivity of pipe between axial and transverse deformation

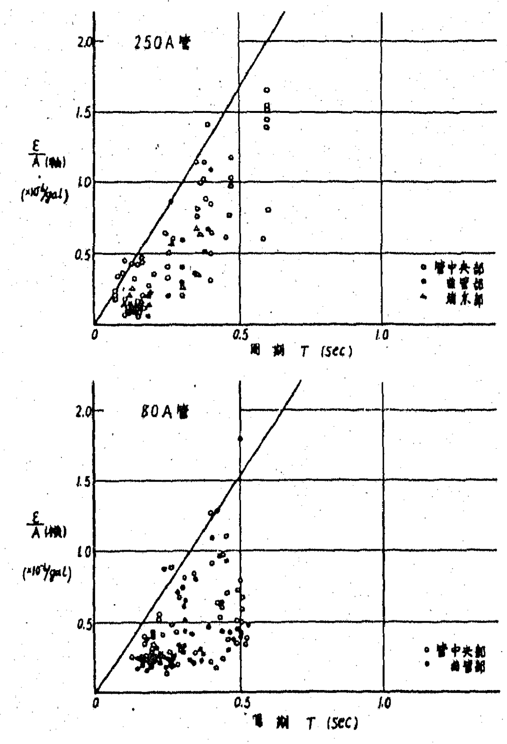

Fig. 5.5 The observed relation of Eq.(5.7)

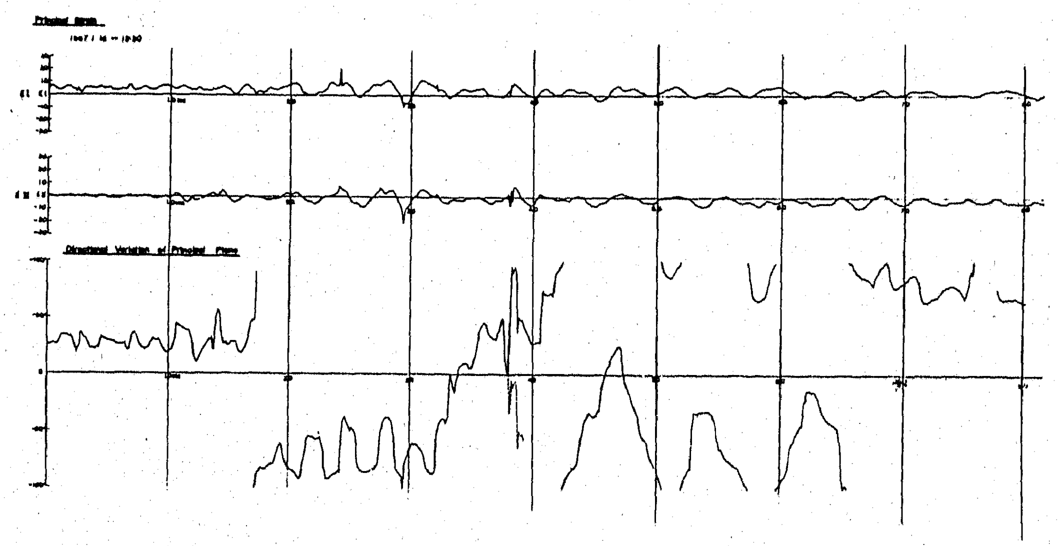

Fig. 5.6 Variation of principal strain and principal angle calculated from ground strains at the surface

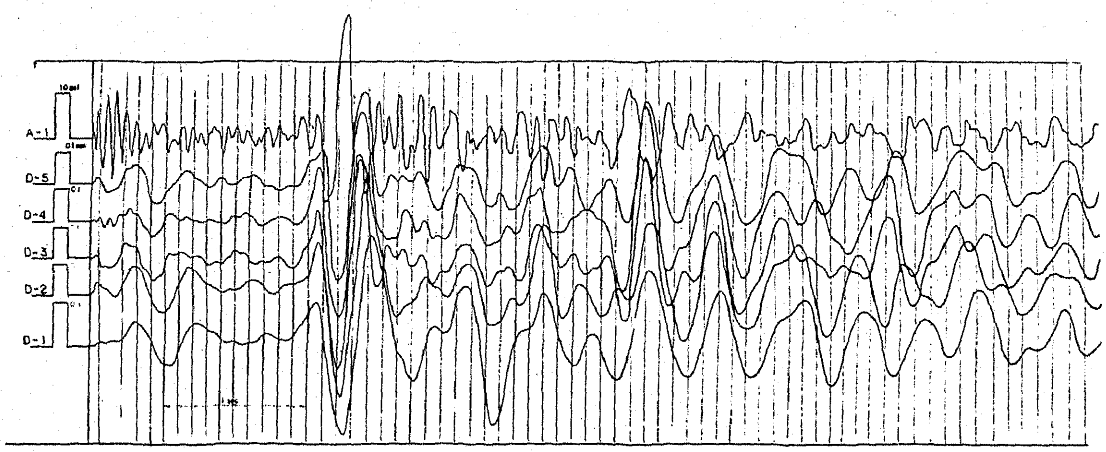

Fig. 6.1 A record of ground displacements at the surface (axial direction)

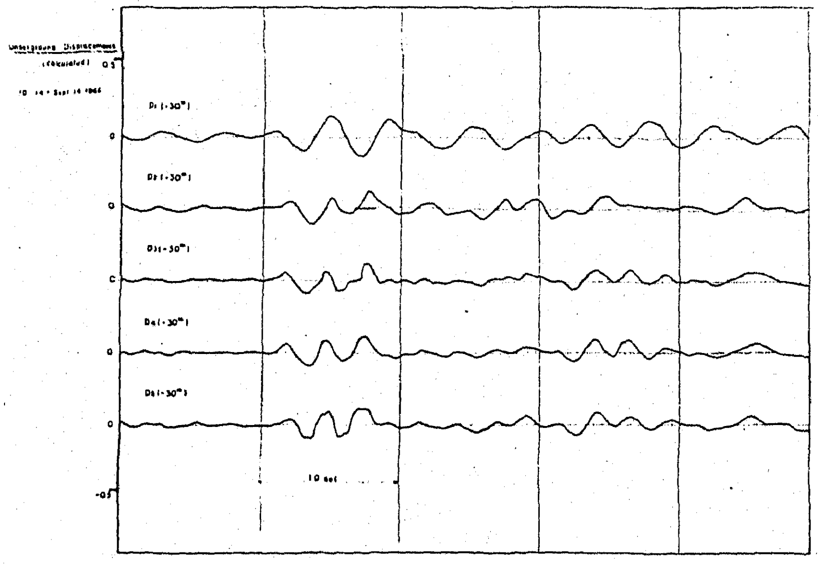

Fig. 6.2 Underground displacements calculated from the surface displacements

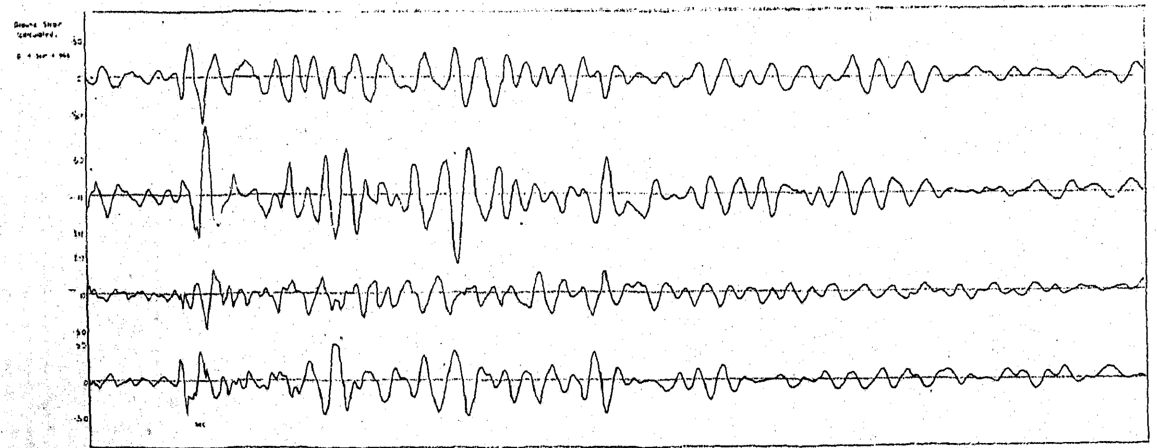

Fig. 6.3 Ground strain calculated from the surface displacements

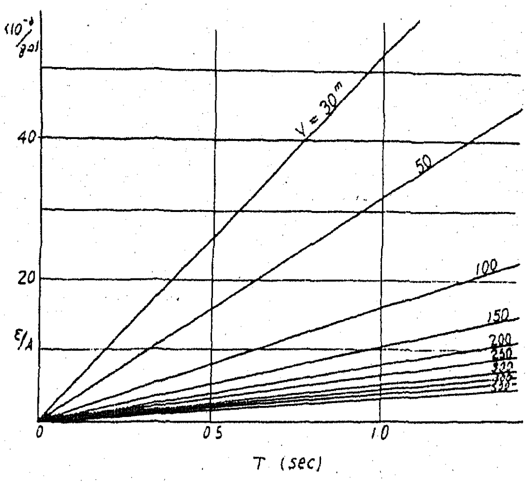

Fig. 7.1
Strain of underground pipe lines

Table 2-1 Number of Earthquakes

		Matsushiro						Nagano					Sakai				
		No.	I	II	III	IV	V	I	II	III	IV	V	I	II	III	IV	V
'65	8	3,739	69	1				1									
	9	8,744	176	18				12	2								
	10	19,839	1,021	111	11			7	2	1							
	11	25,186	2,327	343	51	8		30	7	10	2						
	12	22,583	2,471	356	38	2		18	6	2							
'66	1	22,917	2,451	293	27	2	1	20	3	3	1		3		2		
	2	18,727	1,710	162	22	1	1	21	8	3			2	2	1		
	3	48,576	4,903	428	33	3		65	17	5			4	5			
	4	119,035	10,897	968	84	10	4	310	92	48	2	1	17	13	3		
	5	82,544	7,470	517	42	8	1	346	103	26	7		32	19	9	3	
	6	53,629	4,091	271	19	1		167	65	23	4		14	21	3	1	
	7	34,404	2,613	135	7	1		122	52	8	1		14	4	1	1	
	8	63,313	5,750	409	43	7	1	172	76	11	6		39	22	4	1	
	9	62,171	5,856	360	19	4		181	65	10	2		47	17	4	2	
	10	19,686	1,190	68	4			72	26	2	3		8	12	3	6	
	11	11,913	622	32				35	18				14	2	2		
	12	7,371	446	24	1			15	13	2			2	5	1		
'67	1	7,141	385	10	1			14	7	2			57	18	4	3	3
	2	10,707	584	14	2			12	7	4			155	62	11	2	1
	3	5,640	284	11	1			18	10	1			55	16	1		
Total		653,908	55,766	4,542	407	47	8	1,638	579	161	28	1	463	218	49	19	4

Table 3.1 Dimensions of pipe lines.

Pipe	Shape	Weight (kg/m)	Length (m)	
250A	Circutar Dia. 267.4^{mm}	42.4	91	Steel pipe with bend and man hole
80A	Circutar Dia. 89.1^{mm}	8.7	70	Steel pipe
Asbestine	Rectangular 500×630^{mm}	612	44.1	Asbestine pipe (ø125 x 4) surrounded with concreete, with man hole