Earthquake Engineering, Tenth World Conference © 1992 Balkema, Rotterdam. ISBN 90 5410 060 5

Seismic observation of a pipeline buried at the heterogenous ground

H. Ando, S. Sato & N. Takagi
Fundamental Technology Research Laboratory, Tokyo Gas Co., Ltd. Japan

ABSTRACT: Earthquake observation has been carried out in a newly developed town in order to make clear mechanism of the seismic behavior of buried pipeline. Site of the observation had flatly reclaimed to cut the upper part of slope ground and fill its deposit in the lower part of the slope ground. The observation shows that seismic motion of the embanked ground were more extremely amplified than that of the original ground. This is considered that the embanked ground vibrated sympathetically during the principal wave motion due to upward propagation of shear wave from base rock. These different responses gave large relative displacement and axial strain to the pipeline in the vicinity of the boundary between the two types of ground mentioned above. These responses were ascertained by a finite element calculation, and gave a good agreement with the measurement.

1 INTRODUCTION

The 1978 Off Miyagi Prefecture Earthquake in Japan gave heavy damage to gas distribution pipelines in the boundary grounds where hills had partly been cut and their deposit had been embanked in swamps. The boundary ground is for convenience called the 'heterogeneous ground', which often exists in newly developed towns for residential estate. Although exhaustive effort has so far been made by many researchers, there was few studies to evaluate the mechanism of seismic behavior of pipelines to cause damage(Tsukamoto et al.(1985) and Nishio et al. (1988)).

In the mean time, necessity of some practical and effective guideline is being requested for earthquake protection scheme of pipeline system, in particular for the heterogeneous ground.

Earthquake observation has then been carried out for a few years at Tama Newtown in Tokyo, where the heterogeneous grounds exist in places. The paper mainly describes the seismic behavior of pipelines on the basis of measurement during earthquakes occurring in the period, and analytical discussion associated with finite element calculation.

2 LOCATION OF INSTRUMENTATIONS AND SOIL PROFILE

Figure 1 shows location of instrumentations and a brief soil profile in the observation site. The land was reclaimed almost flatly by cutting a hilltop and filling a valley. A welded steel pipeline of 100mm diameter was embedded at a depth of about 1.2m so that it could cross the boundary between the original and the embanked grounds. T-shaped steel pipes were jointed to both ends of the straight pipeline to prevent slippage between the pipeline and the ground. The pipeline

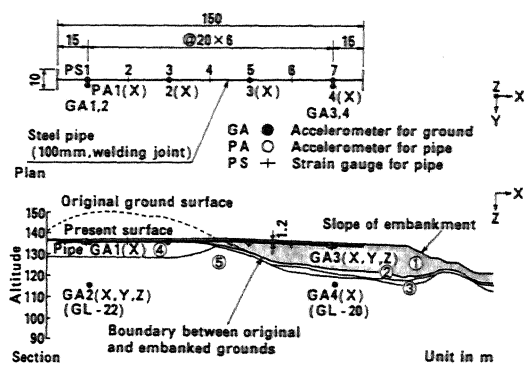

Figure 1. Location of instrumentations and a brief soil profile in the observation site.

were equipped with seven strain gauges on its surface at an interval of 20m and with four accelerometers at an interval of 40m as shown in the figure. Further four accelerometers were installed in both the original and embanked grounds; two of them at the same depth of the pipeline and the others at the base rock as shown in the figure.

Soil profiles are as follows; The embanked ground has four layers of loam(①) mainly consisting of fill bank, loam(②), humic soil(③) and fine sand(⑤), while the original ground has a couple of layers of weathered gravel(④) and fine sand(⑤). The PS logging exploration provides that the average velocity of shear wave(Vs) gives 166m/sec in the embanked ground, and 274m/sec in the original ground. The original ground is a little softer than seismic base rock where Vs is generally assumed as 300m/sec or more. A natural frequency in the embanked ground is estimated to be of 2.3 to 2.9Hz from measurement of a micro tremor and calculation in the system having freedom of a single degree.

3 CHARACTERISTICS OF SEISMIC MOTION IN THE HETEROGENEOUS GROUND

3.1 *Results of measurement*

Discussion will be made from record of accelerations obtained in the surface layer. As be stated in later, only result of the X-direction is referred in this paper. Several earthquakes of 10gal or more have been observed during the period. Comparison of acceleration records between GA1X and PA1X or between GA3X and PA4X suggests that the seismic behavior of the pipeline on the same location is approximately similar to that of ground(Ando et al.(1991a)).

The paper concerns about two big earthquakes. The first record(No.1) was obtained during the earthquake of 17th December 1987, whose epicenter was beneath eastern sea of Chiba Prefecture. The distance is of 104km far from the observation site. The second record(No.2) was obtained during the earthquake of 18th March 1988, which occurred in the eastern part of Tokyo Metropolitan area. The epicenter was 25km away from the site.

Figure 2 shows time histories of the ground accelerations(GA1X and GA3X) in both the original and the embanked grounds. Seismic motion were more amplified in the embanked ground than the original grounds, especially during the period of principal wave. In order to examine characteristics of seismic motion across the boundary between the two types of grounds, running spectra of acceleration of GA1X and GA3X are calculated in Figure 3. Spectra intensity is

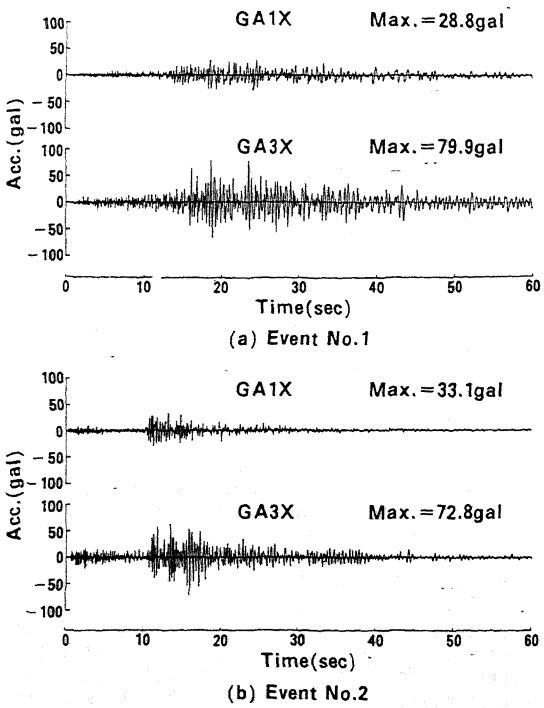

Figure 2. Time histories of the ground accelerations in both the original and the embanked grounds.

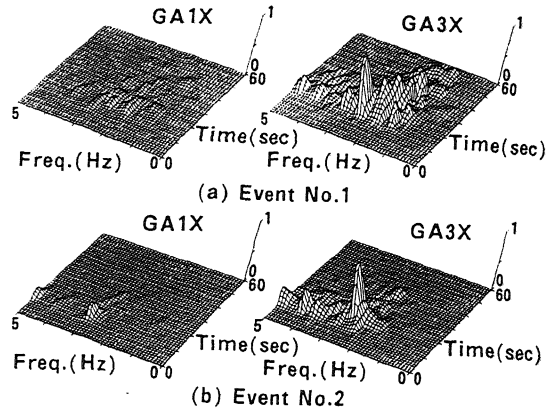

Figure 3. Running spectra of acceleration of GA1X and GA3X.

normalized in each earthquake with the maximum of GA3X. The running spectrum of GA3X is remarkably larger in the frequency band of 2 to 3Hz(largest at 2.6Hz) during the principal wave, while that of GA1X has no distinct value at any frequency. This means that seismic motion tended to be more amplified in the embanked ground than in the original ground.

The predominant frequency above corresponds to the natural frequency in the embanked ground which was mentioned previously. It is, therefore, supposed that the sympathetic vibrations in the embanked ground caused the above motion throughout all the earthquakes(Ando et al.(1991b)). In other words, the ground motion was mainly excited by shear wave which propagates upwards from the base rock.

In order to confirm this estimation, cross correlation was calculated about any two acceleration records. The calculation provides apparent propagating velocities as follows. During the principal wave, the apparent propagating velocities in the vertical direction(GA2X to GA1X, or GA4X to GA3X) are almost equal to the average Vs measured by the PS logging exploration, while they are infinite during the subsequent wave. On the contrary, those in the horizontal direction(GA1X to GA3X, or GA2X to GA4X) are infinite during the principal wave, while they are almost equal to the velocities of surface wave of 1km/sec or more during the subsequent wave. This suggests that the shear wave were predominant during the principal wave.

3.2 *Results of FE calculation*

For the purpose to investigate detailed seismic motion in the heterogeneous ground and to compare with the results of measurements, dynamic analysis using program code 'FLUSH' was carried out, where shear modulus and damping factor for soil materials are considered as strain dependent properties. Figure 4 shows mesh of a FEM model. Four kinds of calculations were done by putting the two experienced acceleration records as well as those of the El Centro Earthquake to the bottom boundary. The maximum accelerations are of approximately 25gal for the first two earthquakes, and of 25gal and 150gal for the wave of the El Centro Earthquake. The El Centro wave of 25gal was compelled to be similar order to those of the

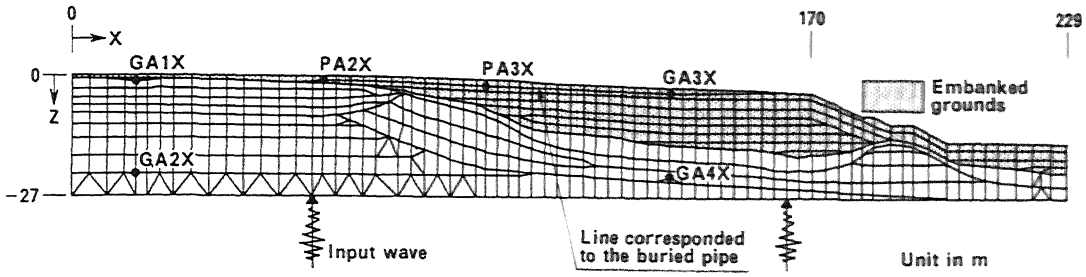

Figure 4. Mesh of a FEM model in the observation site.

first two earthquakes.

Figure 5 gives four profiles of maximum ground accelerations along the pipeline as well as the measurements. Although the first two calculations are twice or less larger than the measurements obtained by the two earthquakes, the tendency is similar that the maximum acceleration is larger in the embanked ground than the original ground. While GA3X/GA1X =2~3 in the measurement, its ratio is about 2 or less in the calculation. That is to say, the seismic motion around the heterogeneous ground is more excited as thickness of the embanked top layer becomes larger. Generally speaking, if the thickness keeps constant, the maximum acceleration does not vary. However, the maximum accelerations seems to decrease around the shoulder of the slope in the case of observation site.

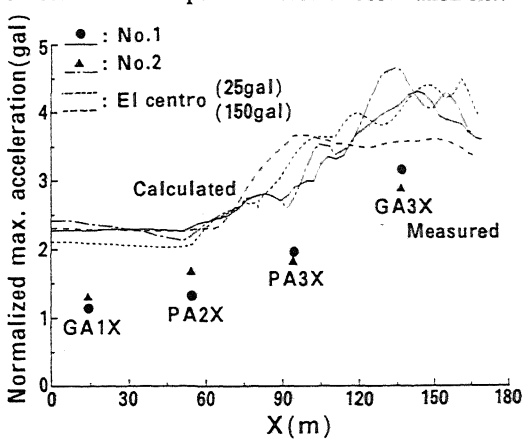

Figure 5. Four profiles of maximum ground accelerations calculated along the pipeline.

This is supposed to be affected by local characteristics of seismic motion at the slope surface.

Calculation for the El Centro Earthquake of 25gal also gives the similar result to those of the first two calculations. This suggests that the maximum acceleration in the heterogeneous ground might be evaluated irrespective of the mode of a given wave.

On the other hand, the forth calculation for the El Centro of 150gal yielded 350gal to the original ground, and 550gal to the embanked ground. The calculated ratio corresponding to GA3X/GA1X was 1.6 or less. The ratio became slightly lower in comparison to those of the other calculations, because the shear modulus and damping factor of soil greatly depend on strain of the soil. This means influence of the strain dependency is larger in the embanked ground than in the original ground. However, since all the four calculations show the similar tendency, the finite element prediction will be able to evaluate the characteristics of seismic ground motion.

4 THE BURIED PIPELINE BEHAVIOR IN THE HETEROGENEOUS GROUND

4.1 *Results of measurement*

When examining records of the seven strain gauges of PS1 to PS7 in the pipeline, it will be realized how the pipeline responded to seismic motion of the ground. Throughout all the earthquakes experienced the axial components of strains were approximately 10 times as large as the bending components, irrespective of their locations. Tsukamoto et al.(1985) also stated that the axial force(strain) might be a predominant factor for

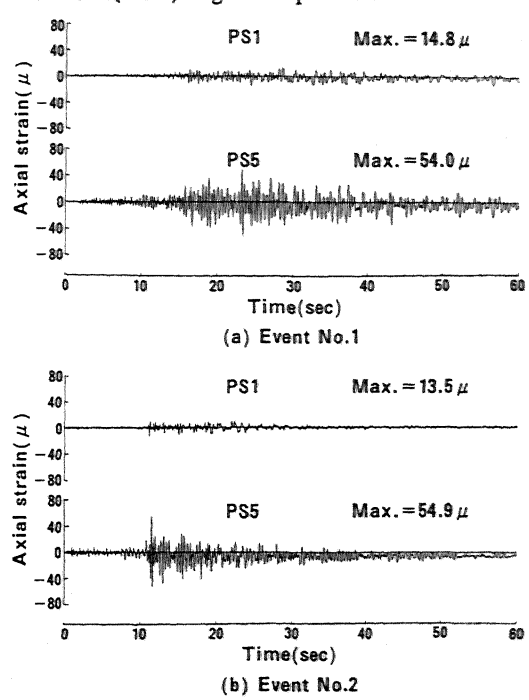

Figure 6. Time histories of the axial strains of PS5 and PS7.

evaluating seismic damage of the buried pipeline.

Figure 6 shows time histories of the strains of PS5 and PS7, which located in the original and the embanked ground, respectively. Both the strains were more amplified during the principal wave than during the subsequent wave. The strain of PS5 was extremely larger than that of PS1.

Two point marks in Figure 7 shows distributions of the maximum axial strains along the pipeline during the two earthquakes. It should be noted that strains of PS5 to PS7 in the embanked ground were much larger than those of PS1 to PS3 in the original ground. The strains of PS1 to PS3 present relatively small values in relation to those in the embanked ground. The strains gradually increased as the thickness of the upper embanked layer becomes larger. The distributions had peaks at PS5 or PS6, whose locations were a little apart from the boundary of the grounds. The strains of PS7 near the shoulder tended to be amplified again.

Tsukamoto et al.(1985) concluded that the maximum strain took place around the boundary, where thickness of the upper embanked layer changes dramatically. However, PS7 considerably strained in case of this observation. This is supposed to be affected by local characteristics of seismic motion at the slope surface, and by the effect of the T-shaped configuration at the end of the pipeline. Four lines in Figure 7 show instantaneous distributions of axial strain at the moment when the strain of either PS5 or PS7 had the maximum during each earthquake. When PS7 took the maximum value, the distribution during each earthquake increased monotonously from PS1 to PS7. This mode may be influenced by the above side effects. On the other hand, when PS5 strained at the maximum, the side effects did not appear in the distributions.

Since seismic motion due to the shear wave should be amplified more significantly in the embanked ground than in the original ground, the different responses give large axial strain to the pipeline in the vicinity of the boundary.

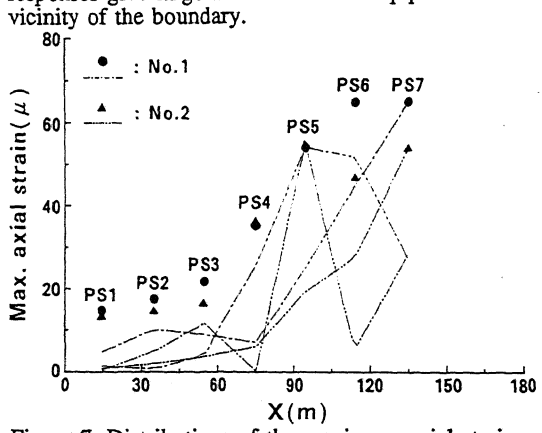

Figure 7. Distributions of the maximum axial strains measured along the pipeline.

4.2 *Results of FE calculation*

The FE analysis previously presented in 3.2 was again used to examine the influence of the characteristics of seismic motion upon the behavior of the buried pipelines. The analysis comprises of the following two procedures. The first one is to obtain an instantaneous distribution of horizontal ground displacement when horizontal ground strain along the pipeline becomes the largest. The second one is to calculate the axial pipe strain by giving the instantaneous distribution to the pipeline. While the first was calculated by the 'FLUSH', the second was also done by the computer program 'ANFS', which is based on theory of a beam on elastic foundations and can presume the beam as material of non-liner elasticity.

The yield tensile stress(σ_y) for the steel pipe is given as 300MPa, which is approximately equivalent to 1,430μ strain. Horizontal coefficient of subgrade reaction(K_1) for the buried pipe is assumed as 6MN/m^3, and vertical one(K_2) as 18MN/m^3 on the basis of $K_2/K_1 \fallingdotseq 3$ principle, which is given on the '*Guideline for the earthquake protection scheme of pipeline system*'(Japan Gas Association(1982)).

Figure 8 shows the results associated with the two earthquakes experienced. Three different curves in the figure mean as follows:-

S1: distributions of the horizontal ground strain at the peak at each location,
S2: instantaneous distributions of the horizontal ground strain when the maximum value occurred,
S3: distributions of axial pipe strain.

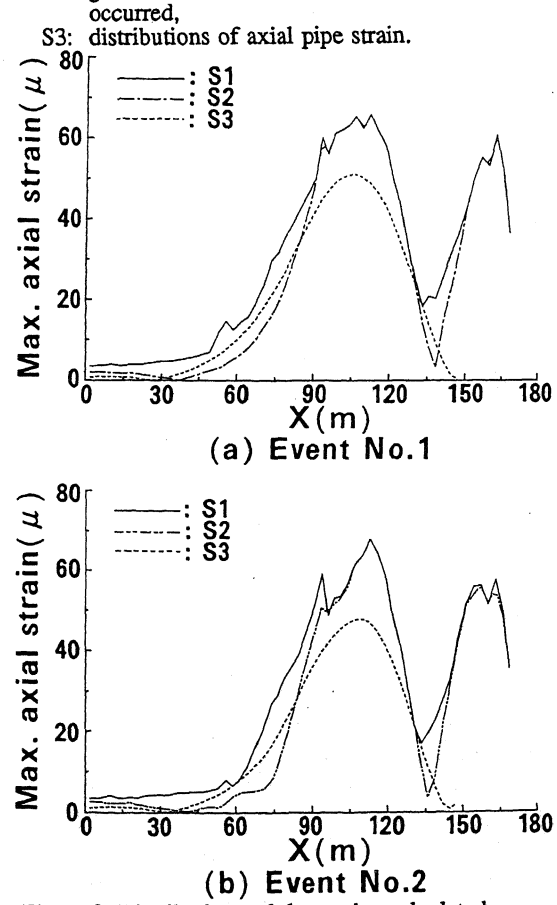

Figure 8. Distributions of the strains calculated with the two earthquakes experienced.

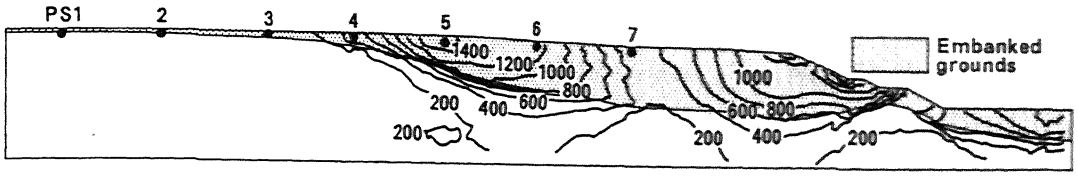

Figure 9. Contour of the maximum horizontal ground strain for the El Centro Earthquake having the 150gal maximum acceleration.

The curve S1 has the maximum between PS5 and PS6, and it increases again in the vicinity of the shoulder of the embankment. The curve S2 is approximately similar to the curve S1 except the vicinity of the shoulder. Since there is little difference between the curves S1 and S2, the axial pipe strain(S3) can adequately be evaluated when the curve S2 is taken into account. The calculation shows that the maximum axial strains occurred between PS5 and PS6. They are 50.9μ and 47.5μ for the earthquakes No.1 and No.2, respectively. The calculations are a little lower than the measurements. The reason is supposed as follows:-

1) The surface wave is not taken into the calculation.
2) The calculated ratio GA3X/GA1X is lower than that of the measurement.

Nevertheless, the FE analysis gives good agreement with the measurement that the strain is more amplified in the vicinity of the boundary, and that only small strain occurs in the region where the thickness of embanked soft ground holds constant.

Although the calculation did not clarify amplification of axial strain at PS7 especially for the earthquake No.1, the strain was possibly affected by the local seismic motion due to the surface wave. Because component of the surface wave in the principal portion could be much larger during the earthquake No.1 than the earthquake No.2.

The FE analysis shows that the shear wave is more significant factor than the surface wave to strain the pipe in the heterogeneous ground. This is realized by some investigation(Tsukamoto et al.(1985)) of earthquake that the shear wave was the main cause of pipe damages.

Behavior of the pipeline is predicted also for the El Centro Earthquakes. In case of the 25gal maximum acceleration, the strain behavior is almost similar to that of S3 in the figures. Therefore, it may be possible to evaluate behavior of the pipelines without considering the wave form of earthquake nor characteristics of the seismic motion.

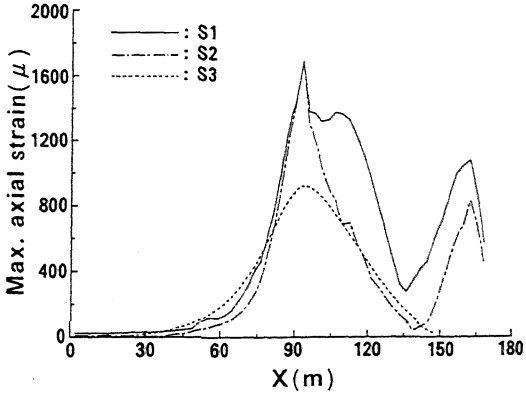

Figure 10. Distributions of the strains for the El Centro Earthquake of 150gal.

Figure 9 shows contour of the maximum horizontal ground strain for the El Centro Earthquake having the 150gal maximum acceleration. The strain is more amplified in the vicinity of the boundary as well as at the shoulder of the embankment.

Figure 10 shows calculated results for the El Centro Earthquake of 150gal similar to Figure 8. The ground strains(S1 and S2) are extremely amplified up to 1,688μ around the boundary of the grounds. The axial pipe strain(S3) increased to 924μ.

5 CONCLUSION

The following remarks are concluded from the observation carried out in this study. The strain of the pipeline becomes larger in the heterogeneous ground rather than in the soft ground of constant thickness. This is caused by upward propagation of the shear wave from the base rock, which may amplify the seismic motion more significantly in the embanked soft ground than in the original hard ground. On the other hand, the surface wave has little effect on the pipeline. These different responses give large relative ground displacement, and consequently significant axial strain to the pipeline in the vicinity of the heterogeneous ground. The finite element analysis gives good agreement with strain measurements of the ground and the pipeline.

REFERENCES

Ando, H., Sase, T., Takagi, N. & Kasahara, K. 1991a. Study on seismic behavior of buried pipeline. Report of R & D Institute of Tokyo Gas Co., Ltd. 30: 247-265.(in Japanese)

Ando, H. & Sase, T. 1991b. Influence on the buried pipeline due to characteristics of seismic motion in the heterogeneous ground. Proc. of 21th JSCE Earthquake Engineering Symposium. Japan: 49-52. (in Japanese)

Japan Gas Association. 1982. Guideline for earthquake protection scheme of gas pipeline.(in Japanese)

Nishio, N., Hamura, A. & Sase, T. 1988. Earthquake observation of a buried pipeline in a non-uniform ground. Proc. of 9th WCEE. Japan: 23-28.

Tsukamoto, K., Nishio, N. & Hamura, A. 1985. Study of pipeline response to earthquake. Report of R & D Institute of Tokyo Gas Co., Ltd. 29: 69-91. (in Japanese)