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# EARTHQUAKE OBSERVATION OF A BURIED PIPELINE IN A NON-UNIFORM GROUND

Nobuaki NISHIO[1], Atsushi HAMURA[1] and Takeshi SASE[1]

[1]Research and Development Institute, Tokyo Gas Company, Ltd., Minato-ku, Tokyo, Japan

## SUMMARY

An earthquake observation was carried out on a buried pipeline that crosses a cut-and-fill boundary in a recently developed residential lot. This paper describes the observed data and its analysis, and discusses the effect of ground conditions on seismic strain in the pipeline. Each set of data indicates that non-uniformity in ground structure is a significant cause of seismic strain in the pipeline, while the effect of a horizontally propagating wave (surface wave) is shown to be much less significant.

## INTRODUCTION

Although numerous studies have been conducted on the seismic behavior of buried pipelines, most of those studies presuppose that dynamic (seismic) strain in a pipeline is caused by an elastic wave that travels along the pipeline axis. It is obvious, however, that an elastic wave only produces elastic strain that cannot cause damage to (or a plastic strain in) the pipeline. On the other hand, the actual damage to pipelines indicates that the local ground condition--abrupt changes or non-uniformity in the superficial ground structure, except for the case of soil liquefaction--bears a strong correlation with the seismic deformation in the pipeline.

In order to establish practical as well as effective guidelines for seismic design of pipeline systems, it is essential, therefore, to make clear the mechanism of seismic behavior of a pipeline in relation to the local ground conditions. For this purpose, we have been carrying out earthquake observations in several locations (Refs. 1,2,3). The results showed the effect of horizontally propagating waves (or surface waves) was much less significant than the effect of non-uniformity in ground structure. Above all, the fact was clearly observed at the Nanko-dai observation site that the strain in the pipeline was the greatest at locations where the depth of the soft surface layer was steeply changing (Refs. 2,3). We also performed experiments on ground-pipeline systems by using models that were dynamically similar to the existing ground in which gas distribution pipelines sustained heavy damage during the 1978 Off Miyagi Prefecture Earthquake (Ref. 4). These experiments proved that the non-uniform surface layer could produce considerable strain in a pipeline if the soil were very soft and the degree of non-uniformity (i.e. degree of change in depth of soft layer) were significantly high.

Based on the above studies, Nishio (Ref. 5) proposed an index of non-uniformity (NI) for evaluating the local ground conditions in terms of pipeline-damage susceptibility. It is desirable, however, to obtain additional data on the effect of ground conditions on seismic strain in a buried pipeline. This is so that the significance of non-uniform ground structures can be demonstrated more clearly.

For this purpose, we are carrying out earthquake observation at Tama New-Town in a westward suburb of Tokyo. An arc-welded steel pipeline was laid across a boundary between cut ground and filled ground. A number of sets of data were obtained up to the present; they clearly reflected the effect of ground conditions, i.e. non-uniformity in the soil profile along the pipeline, as expected.

This paper describes the analyses of the obtained data followed by discussions on the effect of ground conditions. Cross correlation analyses on two sets of data were also made, and the characteristics of the incident earthquake waves were discussed.

## GROUND CONDITIONS OF OBSERVATION SITE AND LAYOUT OF INSTRUMENTS

The local topography of the observation site is shown in Figs. 1 and 2, with contour lines for both the original topography and the present state. The land was made nearly flat by leveling the hilltops and filling a valley. One end of the filled ground formed a bank. The shear wave velocity distribution in the ground was also investigated by means of elastic wave exploration (PS logging). The broken line in Fig. 2 indicates the original shape of ground surface. The two lines denoted by letters "a" and "b" indicate discontinuous planes with respect to shear wave velocity. Plane "a" is likely to be the base that corresponds to the natural frequency of the surface layer (about 4 Hz). Plane "b" is likely to be the base corresponding to another natural frequency (about 2.8 Hz). An arc-welded steel pipeline 100 mm in diameter and 150 m in length was

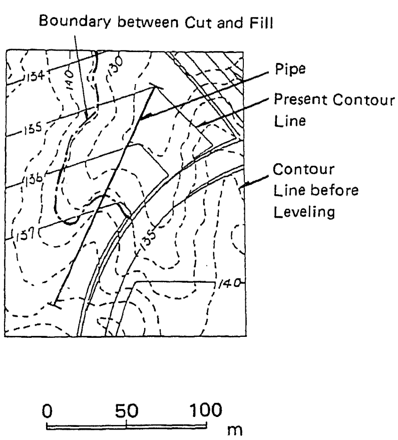
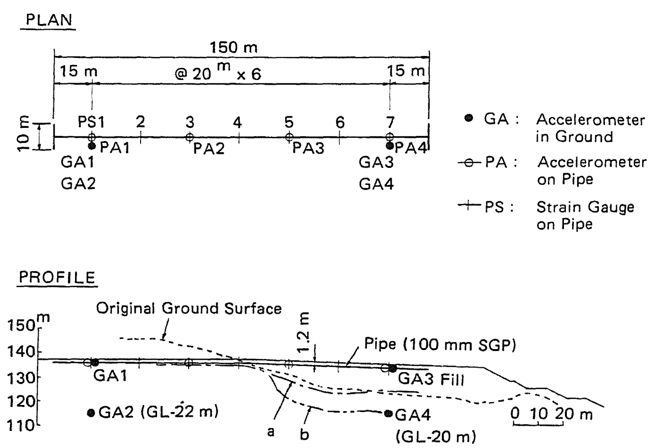



Fig. 1 Topography and Location of Pipe at Observation Site




Lines **a** and **b** indicate discontinuities of shear wave velocity: above line **a**, Vs < 190 m/s; between lines **a** and **b**, Vs = 220-240 m/s; and below line **b**, Vs > 270 m/s.

Fig. 2 Topographical Profile of Observation Site and Layout of Instruments

Table 1 Summary of Twelve Earthquake Records

| No. | Date | Location | Focal Depth km | Epicentral Distance km | Magnitude M | Max. Acc. gal | Max. Strain x$10^{-6}$ | |
|---|---|---|---|---|---|---|---|---|
| | | | | | | | Axial | Bending |
| 1 | 1986 6.24 | S-E Off Bōsō Peninsula | 73 | 149 | 6.5 | 39.6 | 34.2 | 3.3 |
| 2 | 7.4 | South Saitama Prefecture | 141 | 29 | 4.9 | 8.6 | 7.3 | 0.8 |
| 3 | 7.9 | West Kanagawa Prefecture | 13 | 50 | 4.2 | 32.3 | 9.1 | 1.3 |
| 4 | 11.22 | Near Izu-Oshima | – | 102 | – | 32.5 | 23.3 | 2.6 |
| 5 | 12.30 | North Nagano Prefecture | 1 | 171 | 5.9 | 10.0 | 7.4 | 0.6 |
| 6 | 1987 2.6 | Off Fukushima Prefecture | 18 | 273 | 6.4 | 8.7 | 7.6 | 0.7 |
| 7 | 2.6 | Off Fukushima Prefecture | 31 | 272 | 6.7 | 17.0 | 15.5 | 1.4 |
| 8 | 4.7 | Off Fukushima Prefecture | 37 | 292 | 6.7 | 22.9 | 17.4 | 1.5 |
| 9 | 4.10 | S-W Ibaraki Prefecture | 57 | 72 | 5.1 | 18.2 | 17.3 | 1.5 |
| 10 | 4.17 | North Chiba Prefecture | 75 | 70 | 5.1 | 14.6 | 9.1 | 1.0 |
| 11 | 12.17 | East Off Chiba Prefecture | 50 | 104 | 6.7 | 79.8 | 65.1 | 8.2 |
| 12 | 1988 3.18 | East Tokyo Metropolis | 99 | 25 | 6.0 | 72.7 | 55.1 | 6.4 |

laid across the boundary between the cut ground and the filled ground. T-shaped branches, each 10 m in length, were attached to both ends of the pipeline so that slippage between the pipe and the ground would not occur. Four accelerometers (GA1-GA4) were placed in the ground--two of them near the pipe at a depth of 1.2 m and the others at greater depths in the original (undisturbed) ground. Accelerometers were also placed on the pipeline at four locations (PA1-PA4). Seven sets of strain gauges were attached to the pipeline at an interval of 20 m. Two gauges on both sides of a pipe section formed each set. The direction of both gauges was along the pipeline axis so that they could measure both the overall axial strain and the bending strain in the horizontal plane. The earthquake measurements were triggered automatically by an acceleration exceeding 5 gal (gal = cm/s$^2$) in intensity at gauge GA2.

## SUMMARY OF EARTHQUAKE RECORDS

Rough summary of the records  Table 1 summarizes the records of twelve earthquake events that gave relatively high accelerations at the observation site. These earthquake events show wide variation in magnitude, epicentral distance, and in the depth of their source. It is remarkable to note that the bending strain in the pipeline is almost 1/10 the axial strain for all events. This fact agrees with the general understanding that the axial force is the dominant factor contributing to the seismic damage to buried pipelines.

Strain distribution in the pipeline  Fig. 3 shows the distribution of the maximum strains and the maximum accelerations along the pipeline. In this case, the strain is normalized by the average acceleration throughout the length of the pipeline. An average of four maximum accelerations at gauges GA1, GA3, PA2 and PA3 were used to normalize the strain; the accelerations at PA2 and PA3 were assumed to represent approximately the accelerations in the neighboring ground. This average acceleration is considered suitable to represent the seismic intensity at a particular area during an earthquake. This is because the seismic intensity always shows a considerable degree of variation, even within a small area, depending on the geological conditions (such as non-uniformity in the ground structure, the nature of the earthquake, etc.).

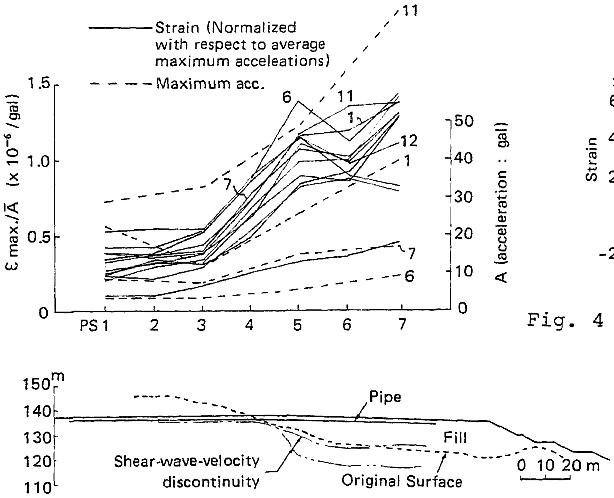



Fig. 3 Observed Strain Distributions along Pipeline (with Examples of Acc. Distribution)

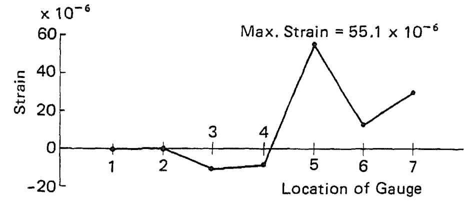


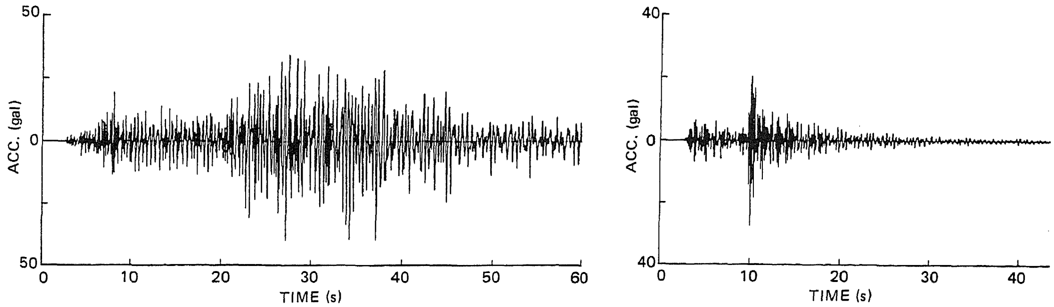

Fig. 4 Instantaneous Strain Distribution During EQ Event No.12 (at the moment when the maximum stain was observed)

The filled part of the ground almost always shows greater acceleration than the cut part. The fact that the acceleration at gauge GA3 always took the greatest value is assumed to be due to the shoulder part of the embankment being shaken more violently than the flat part of the ground. The strain in the pipeline is always greater in the filled part than in the cut part of the ground. It should be noted that the sudden increase in strain from the location of PS4 to that of PS5 obviously corresponds to the sudden change in the depth of the softer surface layer at the corresponding location. The greatest strain usually occurred at gauge PS7. This is assumed to reflect the greater response of the shoulder part of the embankment. Otherwise, the maximum strain is expected to take place at a location closer to the cut-and-fill boundary (such as the location of PS5 or PS6). This is suggested by the instantaneous strain distribution such as is shown in Fig. 4.

## CROSS CORRELATION ANALYSES OF THE OBSERVED RECORDS

Information on the mode of wave propagation can be obtained by carrying out cross correlation analyses on pairs of earthquake records taken at two neighboring locations. Accordingly, we carried out cross correlation analyses on four acceleration records taken by the accelerometers in the ground (i.e. GA1 through GA4) for two earthquake events. One is event No.1 that was at a medium distance (and in a direction almost perpendicular to the axis of the pipeline being observed). The other is event No. 3 that was at a relatively short distance (and in a direction almost parallel with the pipeline axis).

Cross correlations were calculated for both the horizontal and vertical directions (horizontally from GA1 to GA3 and from GA2 to GA4, and vertically from GA2 to GA1 and from GA4 to GA3) for two periods of each event, i.e., the earlier period (main shock) and later period. The waveforms recorded by gauge GA3 (acceleration in the axial direction) for both events are illustrated in Fig. 5. The phase differences that give the maximum values of correlation coefficients, and the apparent phase velocities of earthquake motions (given by dividing the distances between the two accelerometers by the respective phase differences) are listed in Table 2.

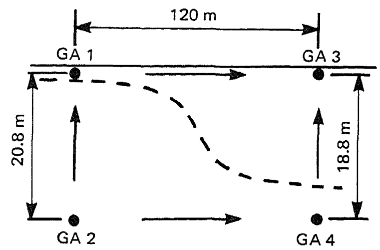



a. Event No.1, S-E Off Bōsō Peninsula     b. Event No.3, West Kanagawa Pref.

Fig. 5 Examples of Earthquake Waveforms

Table 2 Phase Differences and Phase Velocities by Cross Correlation Analyses

| EQ Event | Period | Horizontal | | Vertical | |
|---|---|---|---|---|---|
| | | GA3/GA1 | GA4/GA2 | GA1/GA2 | GA3/GA4 |
| 1 | 20 – 40 $^s$ | 0.009 $^s$ (1333 m/s) | 0.12 $^s$ (1000 m/s) | 0.05 $^s$ (416 m/s) | 0.06 $^s$ (313 m/s) |
| | 40 – 60 | 0.16 (750) | 0.10 (1200) | ≈ 0 (∞) | <0.02 (>940) |
| 3 | 0 – 20 | 0.08 (1500) | 0.03 (4000) | 0.07 (297) | 0.10 (188) |
| | 20 – 40 | 0.05 (2400) | 0.11 (1090) | <0.01 (>2080) | <0.01 (>1880) |




In both events, the apparent phase velocities in the vertical direction show almost the same values as the respective shear wave velocities (Vs > 300 m/s between GA1 and GA2, or in the original ground; and Vs = 170-200 m/s between GA3 and GA4, or in the filled part) during the earlier periods of the events. On the other hand, the horizontal phase velocities are at least as fast as 1 km/s. This clear difference in the phase velocities between the different directions indicate that the upwardly incident wave component (body wave consisting mainly of shear waves) was predominant in the earlier period of both earthquake events. It should be noted that if the surface wave were predominant, phase differences would be very small between the deeper part and the shallower part of the ground, showing apparently very high phase velocity in the upward direction.

During the later period of both events, the apparent phase velocities in the vertical direction are even greater than the apparent horizontal velocities. This fact suggest that either surface waves or natural vibrations in the ground following the main shock predominate during the later period of an earthquake. During this period, however, the earthquake motion is less intense than during the main shock period. Therefore, the surface waves cannot be critical to the seismic damage to pipelines.

## CONCLUSIONS

The fact was demonstrated that non-uniformity in ground structure plays a desisive role in seismic strain in a buried pipeline. It was also evident that the effect of a surface wave (or a wave that apparently propagates in the horizontal direction) on the strain in the pipeline was much less significant.

If the ground is very homogeneous, the strain due to a surface wave will predominate over that due to non-uniformity in the ground. In that case, however, the magnitude of the strain will be insignificantly small because a traveling wave (elastic wave) only produces elastic strain in the ground or pipeline. On the contrary, the response of non-uniform ground to an upwardly-incident earthquake wave can have a crucial effect on a pipeline depending on the degree of non-uniformity; and we have already suggested this fact. This effect of non-uniformity should widely be recognized by the investigators of lifeline systems.

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