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Analysis of seismic ground and pipe strains observed in Chiba, Japan

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ABSTRACT: Data obtained at a seismic array in Chiba, Japan are employed to investigate the spectral characteristics of the seismic strains, the correlation between ground and pipe strains, and the feasibility of estimating strains from acceleration records at various stations within the array. More than 90% of the strain total power is found to be contributed by the frequency range between 0.1 and 6.5Hz. The relative motion between pipe and soil is found to be negligible. Optimum ranges of spacing between stations and of lower cut-off frequency are proposed for the estimation of seismic strains. This procedure is found to be unable to estimate accurately strains of a period longer than about 3 seconds.

1 INTRODUCTION

The seismic behavior of buried linear structures such as pipes and tunnels is strongly affected by the relative displacement of the surrounding soil. Many researchers have tried to estimate the general characteristics of ground strains during earthquakes by using records obtained at different sites during previous earthquakes. However, data from specially designed arrays of closely located strong motion seismographs provide more opportunities to get informative knowledge on the characteristics of the ground and pipe strains.

As the seismic waves travel away from the epicentral region, the ground motions at any two points along the propagation path of the waves are out of phase. If a buried pipeline connects these two points, the out of phase motion will induce strains and curvature in the pipeline. Simplified procedures for the analysis of strains due to the wave propagation effects were first developed by Newmark (1967) and have since been used and/or extended by a number of researchers. It is assumed in this analytical procedure that the pipeline and soil tend to move together, that is, the inertia terms are small and may be neglected. Earthquake induced strains that can be attributed to waves travelling along the ground surface have been studied by Toki (1976) and by Christian (1976). A statistical relation between ground strain and pipeline damage was developed by Shinozuka and Kawakami (1977). The acceleration and strain records obtained at the Chiba Experiment Station were first utilized by Katayama et al.(1984) to calculate and analyze seismic strains and by Sato et al.(1988) to study the relationship between pipe strains and types of propagating waves. More recently, Kameda et al.(1990) used the records obtained at Parkfield, California during the 1989 Loma Prieta earthquake to estimate the seismic strains and compared them to the strains measured directly at the buried pipes.

In this paper, the data obtained at the Chiba Experiment Station of the Institute of Industrial Science, University of Tokyo are employed to study the strains developed in buried pipes and in the adjacent soil medium. The objectives of this study are: the identification of the characteristics of the seismic strains, and the investigation of the correlation between pipe strains and the strains in the surrounding soil, the ill effect of long-period noise, and the feasibility of an accurate estimation of the ground strains from accelerograms recorded at various stations within the array. The effect on strain estimation of such parameters as spacing between stations, long-period noise and intensity of the ground motion is also investigated.

2 STRAIN MEASUREMENT SYSTEM IN CHIBA STATION

The Chiba Experiment Station is located 30 km east of Tokyo. A three-dimensional array with 44 seismometers buried at several depths in 15 boreholes within an area

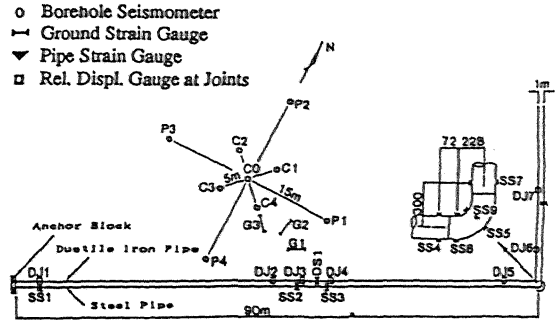


Fig. 1 Strain measurement system at Chiba site

of about 300m x 300m was established in 1982. The topographical and geological conditions of the site are generally simple and the ground surface is almost flat. A strain measurement system consisting of buried pipes of two materials (welded steel and ductile-cast-iron pipes) and three ground strain transducers was also installed at the site. Strain gauges are attached to the pipes to measure the axial and bending strains as well as the relative displacements over the joints. The relative displacements of the ground are directly measured at GL -1.3m by the displacement transducers G1, G2, and G3 which are located in three directions. Figure 1 shows the general layout of the very dense array and the strain measurement system.

More than 160 earthquakes have been recorded since 1982. Using 27 major events with peak accelerations greater than 20 cm/sec^2 or maximum pipe strains larger than 5×10^{-6}, a strong motion database has recently been created by Katayama et al.(1990). This database was employed in the present study.

3 RELATIVE MOTIONS BETWEEN PIPE AND THE SURROUNDING SOIL MEDIUM

The ground strains measured by the transducer G1 and the pipe strains recorded at the strain gauges SS2 and SS3 (see Fig. 1) during the four strongest motions included in the database were utilized to investigate the correlation between pipe and ground strains. The main features of the selected motions are summarized in Table 1. The separation distance between the pipe and the transducer is approximately 5 m. The power spectra of the ground and pipe strains recorded during the event 8722 are shown in Fig. 2. The general characteristics are seen to be basically the same although some reduction is observed in the amplitudes of the spectra corresponding to the ground strain. This reduction is thought to be due to the fact that the measured ground strain is actually the average strain in a length of 3m. Note that the power of the frequencies higher than around 6.5 Hz is very small. Important differences were found in the low range of frequencies, especially for the weaker motions. While sharp peaks were observed for the ground strains, these peaks were not present in the pipe strains. Since their effect is much more noticeable for the weaker motions, they are likely to be the result of long-period noise.

A comparative analysis in frequency domain was carried out using the coherence function, the phase delay, and the Fourier spectrum ratio. Figure 3 shows the results obtained for the four selected events. A very high degree of correlation was found for frequencies up to approximately 6.5 Hz. The coherence function dropped drastically for frequencies higher than 6.5 Hz. Similar characteristics were observed for the phase and the spectral ratio. This is something to be expected due to the very small power corresponding to the frequencies higher than 6.5 Hz.

While a good agreement is found for the event 8722 even for the low frequencies, an absence of correlation can be observed for the weaker motions. Then, it can be

Table 1. Events selected for the analysis

Code	Date	PGA at C0 (gals)	Epic. Dist. (km)	JMA Mag.	Focal Depth (km)	Max. Pipe Strain $\times 10^{-6}$
8307	83.02.27	55.7	45	6.0	72	15.7
8519	85.10.04	82.2	131	6.1	78	18.2
8722	87.12.17	327.1	105	6.7	58	55.6
8816	88.03.18	59.8	28	6.0	96	18.3

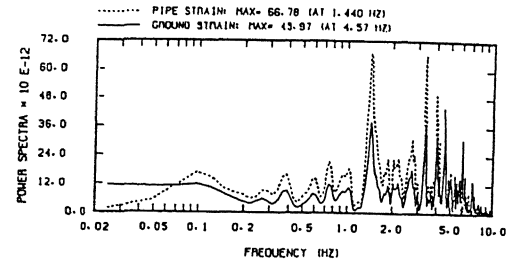


Fig. 2 Power spectra for ground and pipe strains for the event 8722

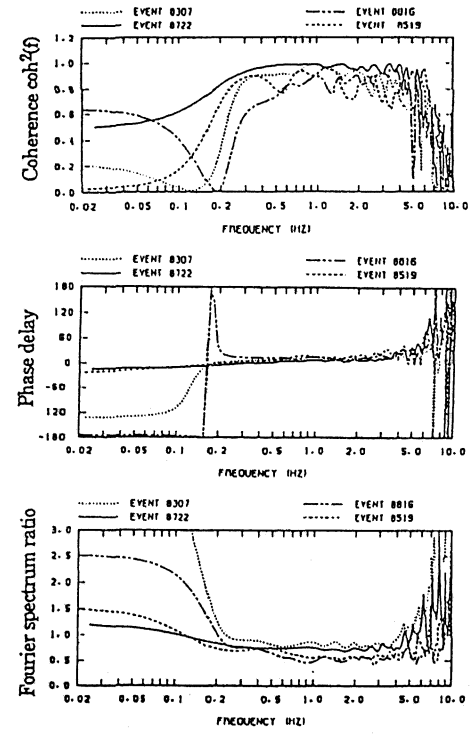


Fig. 3 Correlation between pipe and ground strains for four ground motions

concluded that the level of coherence between ground and pipe strains depends significantly on the strength of the motion and that the differences occur mainly in the range of frequencies corresponding to the long-period contents of the ground strain.

Studies were performed in terms of the cumulative power. It was observed that more than 90% of the total power of the strains comes from the frequency range between 0.1 and 6.5 Hz. After removing the long-period noise, the ground strains were found to be practically the same as those of the surrounding soil.

4 ESTIMATION OF SEISMIC STRAINS FROM ACCELERATION RECORDS

4.1 *One-dimensional method*

Ground displacements evaluated at different stations within the Chiba array are used to estimate the ground strains. The ground displacements are obtained by the two-fold integration of the acceleration records. The average ground strain between two points is calculated from their ground displacements as follows:

$$\varepsilon = \frac{X_1(t) - X_2(t)}{D} \qquad (1)$$

where ε is the average ground strain, $X_1(t)$ and $X_2(t)$ are the ground displacements at stations 1 and 2, respectively, and D is the separation distance between the stations whose values range from 5 m to 30 m in this study. A band-pass filtering of the evaluated strain is performed to minimize the effect of noise. The strain evaluation process is shown in Fig. 4.

The evaluated strains were compared to the strains measured directly by the ground strain transducers to investigate their accuracy.

A comparative analysis in the frequency domain was carried out using the coherence function, the phase delay, and the Fourier spectrum ratio. Good agreement between evaluated strains and directly-measured strains was observed in the frequency range between about 1.0 Hz and 7.0 Hz. On the contrary, poor levels of correlation were found at the low range of frequencies (f<1.0 Hz). Figure 5 shows the power spectra of evaluated and directly-measured strains for the event 8722. An increase of the spectral amplitudes was observed at frequencies lower than 1.0 Hz for the evaluated ground strain and this increase reached very high levels for frequencies lower than 0.5 Hz. The comparison of evaluated strains and directly-measured strains performed for the four events under consideration is shown in Fig. 6. The separation distance D was kept constant at 21.2 m in all the cases. The cut-off frequency was 0.1 Hz. The comparison was carried out in the direction of the transducer G3. The directly-measured strains and the evaluated strains were taken as the input function and the output function, respectively.

In general terms, a slightly better level of coherence was found for the event 8722, which is the strongest among the selected earthquakes. However, the intensity of the motion was not found to be a decisive parameter of the level of correlation between evaluated and directly-measured strains.

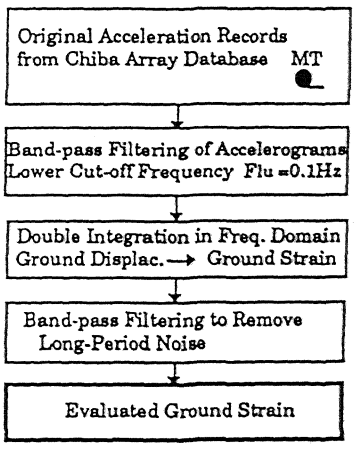


Fig. 4 Procedure for evaluation of ground strain

4.1.1 *Effect of separation distance on ground strain estimation*

The ground displacements that were determined in two directions at nine boreholes of the Chiba array were em-

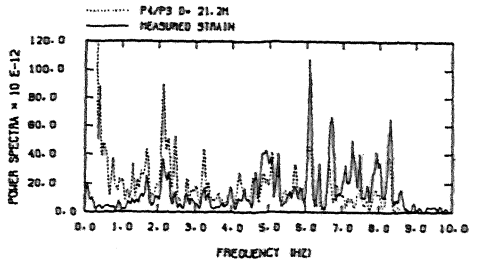


Fig. 5 Power spectra of evaluated and directly measured strains for the event 8722

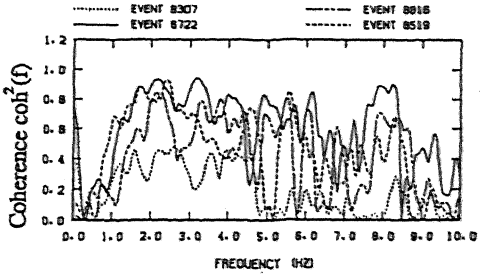


Fig. 6 Correlation between evaluated and measured ground strains for four events

ployed to investigate the effect of the separation distance between two stations on the accuracy of the evaluated strain. Data recorded during the four selected earthquakes were used in the analysis. The results are presented in Fig. 7. The level of correlation between the evaluated strains and the directly-measured strains is expressed in terms of the maximum strain ratio, SR, which is defined as the ratio of the maximum evaluated strain to the maximum directly-measured strain.

A strong scatter is observed for the short separation distances. The scatter decreases as the separation distance between stations becomes larger. The scatter observed for short separation distances may be attributed to the very small relative displacements between the soil particles within short distances. The small relative displacements make the strains evaluated by this procedure more sensitive to noise due to the low signal-noise ratio. The optimum spacing for the evaluation of the ground strain ranges from about 20 to 30 m.

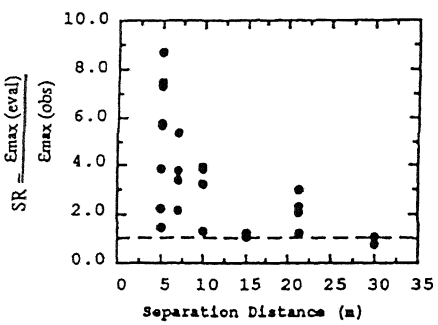
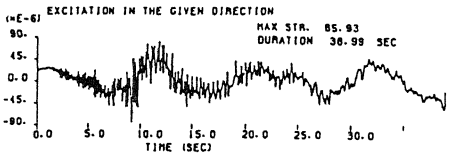


Fig. 7 Effect of the spacing between stations on the evaluation of ground strains

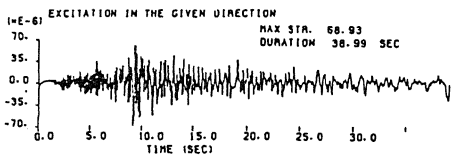
4.1.2 *Effect of long-period noise on ground strain estimation.*

Figure 8 shows the time histories of the ground strains evaluated for the event 8722 in the direction of the transducer G3 using various lower cut-off frequencies. A separation distance of 21.2 m was adopted in all the cases. The ground strain recorded by the transducer G3 is also presented for comparison. The influence of the long-period contents is clearly seen on both the amplitude and the waveform.

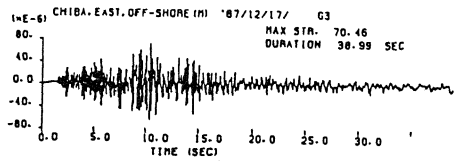
The effect of the application of various cut-off frequencies was studied to remove the long-period noise. It was determined in the previous section that the optimum spacing between stations for the evaluation of ground strains ranges from 20 to 30 m. Hence, ground strains were evaluated for all the selected motions using separation distances within the above mentioned range. The strains were evaluated in the directions of the transducers G2 and G3. The results of the analysis are presented in Fig. 9. It can be concluded that frequencies lower than about 0.40 Hz are to be cut off in order to remove the long-period noise. It is noticed that a strong



a) Evaluated strain; Flu = 0.10 Hz



b) Evaluated strain; Flu = 0.40 Hz



c) Directly measured strain G3

Fig. 8 Time histories of ground strains evaluated for the event 8722 using various low-cut filters

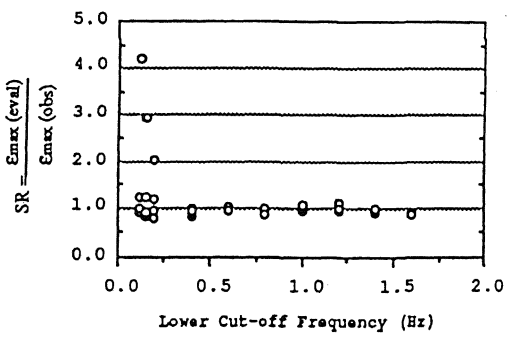


Fig. 9 Effect of the lower cut-off frequency on the evaluation of ground strain from accelerograms

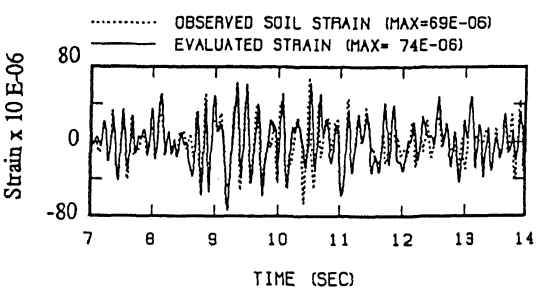


Fig. 10 Comparison of evaluated and measured strains for the event 8722

scatter is observed for the low values of the cut-off frequency. The scatter diminishes for the larger cut-off frequency values.

As an application of the results obtained in this investigation, ground strains were evaluated from acceleration records using the proposed optimum values of separation distance between the stations and cut-off frequency. Figure 10 shows the coincidence between evaluated strains and directly-measured strains for the event 8722.

4.2 *Seismic strains in the plane from acceleration records*

The determination of ground strains from relative displacements at two stations does not allow the estimation of the strains in any arbitrary direction nor the estimation of shear strains. Hence, the strains are evaluated in the plane by applying the finite element method's concept with a triangular element. The values of displacements as functions of time are prescribed at the nodal points and a solution of the strain as a function of time is sought inside the element. Linear forms are adopted for the shape functions so that constant averaged ground strains are estimated within the element.

The evaluated strains are compared to the strains measured by the transducers G1, G2, and G3 and also to those recorded at the surface of the buried steel pipe. The directions of the principal strains and the amplitudes of the maximum axial and shear strain are calculated by the relations for the state of plane strain.

The effect of the size of the element was analyzed using the records obtained at 9 stations during the selected four events. A new parameter, the average length defined as the average of the lengths of the sides of the element, is introduced to represent the size of the element. Its value ranges from about 5m to about 25m in this study. Figure 11 shows the results obtained for three of the considered motions in the direction of G3. The level of agreement between the evaluated and the observed strains is expressed again in terms of the maximum strain ratio SR. While the level of agreement is found to be similar for the events 8816 and 8519, a relatively better agreement is observed for the strongest motion, 8722. However, the scattering for the small elements remains very strong due to the low signal-noise ratio that occurs when the spacing between stations is too small. The scattering decreases for larger elements and the best results are found for elements having an average length ranging from 20 to 25m.

The ill effect of the long-period noise and the effectiveness of its removal by low-cut filtering the evaluated strain were investigated. Figure 12 shows the results obtained for three of the above mentioned events. The value of the low-cut frequency varied from 0.08 to 1.0Hz. The influence of the intensity of the motion is clearly observed. While the effect of the long-period noise is easily removed for the strongest event (8722), little improvement is achieved for the weakest motion (8816). In any case, it can be concluded that strains of a frequency lower than about 0.3Hz, that is, of a period longer than about 3s, cannot be estimated accurately by using this procedure.

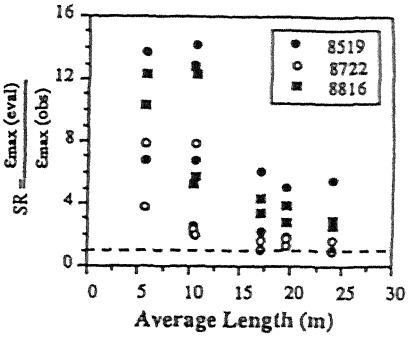


Fig. 11 Effect of element size on strain estimation

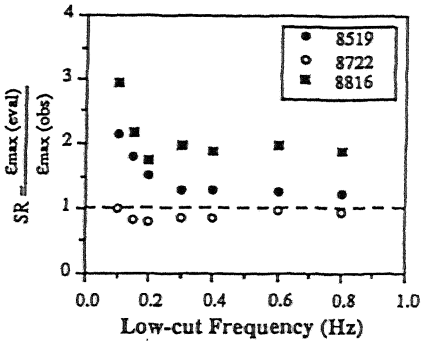


Fig. 12 Effect of low-cut filtering on strain estimation

After removing the ill effect of the long-period noise and choosing a suitable size for the element, the seismic strains in the ground and also at the surface of the buried steel pipe were estimated very satisfactorily. A comparison of the evaluated strain and the strain measured at gauge SS2 during the event 8722 is presented in Fig. 13.

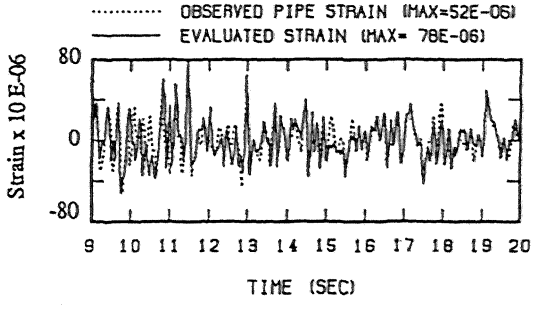


Fig. 13 Comparison of evaluated and measured pipe strain for the event 8722

The variation of the maximum axial and shear strains during the motion was also evaluated using the acceleration records. These parameters may be effectively used for the design of underground structures.

5 CONCLUSIONS

The seismic strains observed in the ground and at the surface of a buried steel pipe at the Chiba Experiment Station were employed to identify the spectral characteristics of the seismic strains, assess the reliability of the recorded strains, and investigate the correlation between pipe and ground strains. The four strongest motions recorded so far were used in the analysis. It was found that more than 90% of the total power of the strains comes from the frequency range between 0.1 and 6.5 Hz. The ill effect of the long-period noise was satisfactorily removed by low-cut filtering the records using a cut-off frequency of 0.1 Hz. The results showed that for the selected motions, the pipe strains are practically the same as those of the surrounding soil and the relative motion between pipe and soil during an earthquake is negligible.

The feasibility of an accurate estimation of the seismic ground and pipe strains from acceleration records obtained from the array was also investigated. Two approaches were adopted. A one-dimensional approach was applied to estimate the average ground strain from the relative ground displacement between two stations separated by a certain distance. A two-dimensional approach was adopted to estimate the strains in the plane. The accuracy of the evaluated ground strains was assessed by comparing them with the ground and pipe strains recorded directly and whose reliability within the frequency range of interest was previously examined.

For the one-dimensional approach, the accuracy of the evaluated ground strains was found to be significantly affected by the separation distance between the stations and also by the long-period noise included in the records. The effect of the intensity of the motion on the level of agreement between evaluated strains and directly-measured strains was not found to be a decisive factor although a relatively better correlation was observed for the strongest ground motion. The effect of long-period noise was magnified when short separation distances between the stations were adopted due to the low signal-noise ratio. The optimum separation distance to be used for the evaluation of the ground strains was found to be in the range between 20 and 30 m for the ground motions employed in this analysis.

For the two-dimensional approach, the finite element's concept was applied with a triangular element with known displacements at the nodal points. The effect of the size of the element and the long-period noise on the strain estimation was investigated. The average length, defined as the average of the lengths of the sides of the element, was introduced to represent the size of the element. The best results were obtained for elements having an average length ranging from 20 to 25m. The effectiveness of the removal of long-period noise by low-cut filtering the evaluated strains was analyzed. It was found that strain contents of a period longer than about 3.0s cannot be evaluated accurately by using this procedure.

Seismic strains were evaluated using the optimum separation distance, size of the element, and cut-off frequency that have been proposed. Good agreement between the strains evaluated by the one- and two-dimensional approaches and the directly-measured ground and pipe strains could be achieved.

The two-dimensional approach for the strain estimation also allows the determination of the directions of principal strains and the variation of the maximum axial and shear ground strains. These parameters may be effectively used in the design of underground structures.

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