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ANALYSIS OF SEISMIC GROUND STRAIN OBSERVED AT THE CHIBA EXPERIMENT STATION

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SUMMARY

The ground strains are evaluated from the accelerograms recorded at the Chiba array. The accuracy of the evaluated ground strains is assessed by comparing them with the strains measured by buried ground strain transducers. A comparative study is conducted in both the time and the frequency domains. The influence of parameters on the evaluated strains, such as the separation distance between the stations, long-period noise, and intensity of the motion, is investigated. Optimum ranges of spacing between the stations and of lower cut-off frequency are proposed. This procedure for ground strain evaluation is found to be unable to estimate accurately the strain contents of a period longer than about 2.5 sec.

1. INTRODUCTION

Lifeline structures such as natural gas and oil pipelines, water and sewage lines, bridges, tunnels, power and communication lines, extend over distances which are long compared to their other dimensions. Consequently, these structures can be strongly affected by the relative displacements of two different points along the lifeline. 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.

Earthquake induced strains that can be attributed to waves travelling along the ground surface have been studied by Toki [1] and by Christian [2]. A reasonable statistical relation was established between ground strain and pipeline damage by Shinozuka and Kawakami [3]. Wright and Takada [4] chose certain pairs of records from the 1971 San Fernando earthquake and observed that the separation distance between two points is an important factor in the evaluation of the ground strain due to the dispersive nature of wave propagation in the ground.

O'Rourke and Castro [5] studied the ground displacements derived from accelerograms recorded at the basement of structures during the San Fernando earthquake and found that the traveling wave assumption is not conservative for short separation distances. Tsuchida and Kurata [6] showed the results of observation of relative displacements along a 2500 m line and Sakurai et al. [7] used a linear array of 5 seismographs placed 30 m apart from each other to study the characteristics of seismic wave propagation and proposed a seismic design criteria of pipelines.

In this paper, the average ground strains are evaluated using the ground displacement time histories determined at various stations within an array. The study employs the data obtained at the Chiba Experiment Station of the Institute of Industrial Science, University of Tokyo. The influence of different parameters on the evaluation of ground strains, such as the separation distance between the stations and the long-period noise included in the records, is investigated. The evaluated ground strains are compared to the directly measured strains in order to assess their accuracy and to investigate the feasibility of an accurate estimation of the ground strains from accelerograms recorded at two different stations.

2. THE CHIBA SEISMOMETER ARRAY AND ITS STRAIN MEASUREMENT SYSTEM

The Chiba Experiment Station is located 30 Km east of Tokyo. The topographical and geological conditions of the site are generally simple with the ground surface being almost flat. The top soil layer is loam with thickness of 4-5 m resting on a 4-meter-thick clayey layer. The clayey layer is underlain by a sand layer. The groundwater table was found to be lower than GL -5 m.

Figure 1 shows the general layout of the boreholes where the accelerometers are placed. The array system is composed of 44 accelerometers which are located at depths ranging from GL -1 m to GL - 40 m.

There is a large triangular network P0-P8-P5 with each of three sides being approximately 300 m. A cluster of eight points surrounds point C0, four of which are only 5 m and the rest are 15 m from C0. The piezoelectric type accelerometers, having a practically flat sensitivity in the frequency range between 0.1 Hz and 30 Hz, are used for the array observation.

The strain measurement system installed at the site consists of buried pipes of two different materials and three ground strain transducers as presented in Fig. 2.

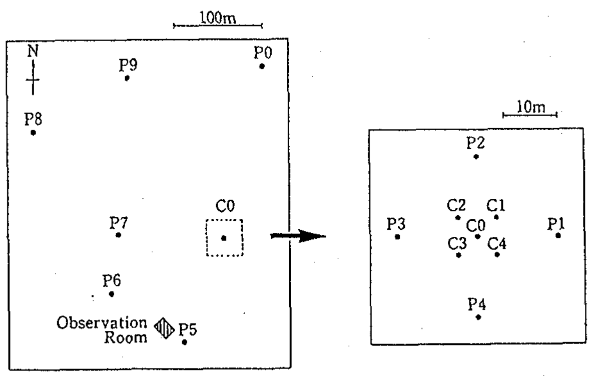


Fig. 1 Layout of boreholes

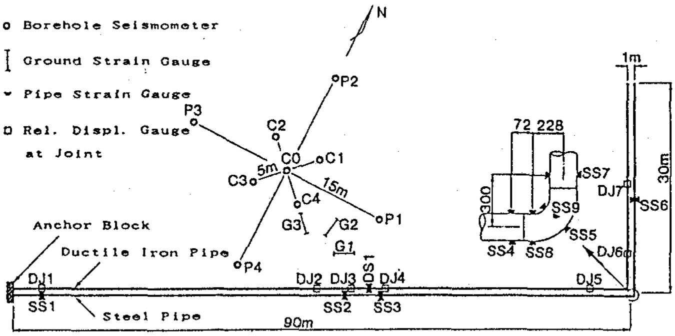


Fig. 2 Strain measurement system at Chiba site

A welded steel pipe and a ductile-cast-iron pipe of diameter 150 mm are buried at GL -1.3 m. Twenty-nine strain gauges are attached to these pipes to measure the strain in the steel pipe, and both the strain and the relative displacement over the joints in the ductile-cast iron pipe. The relative displacements of ground are directly measured at GL -1.3 m by means of three displacement transducers (G1 - G3).

The ground strain transducers measure the changes in distance during earthquakes between two points that are 3 m apart. Details of the transducer are shown in Fig. 3.

More than 160 earthquakes have been recorded since 1982. Based on 27 major events whose peak acceleration is greater than 20 cm/sec^2 or whose maximum steel pipe strain is larger than 5 x 10^{-6}, a strong motion database [8] has recently been created. This database was employed in the present study. Out of this 27 major events, the four strongest records were selected for the analysis of the strains. The main features of these events are summarized in Table 1.

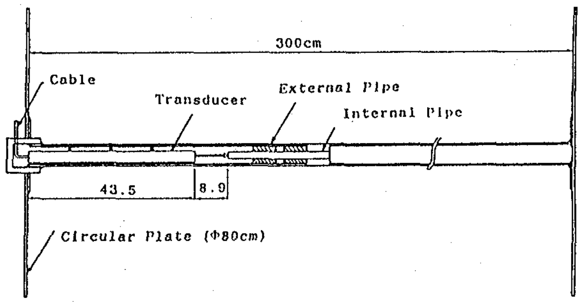


Fig. 3 Details of ground strain transducer

Table 1 Events selected for the analysis

Event Code IEQK	Date	Max. Accel. at C001 (cm/s^2)	Epicent. Distance (km)	JMA Magnitude	Focal Depth (km)	Max. Pipe Strain (x 10E-06)
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

3. ESTIMATION OF GROUND STRAINS FROM GROUND DISPLACEMENTS AT TWO POINTS

The ground displacements evaluated at different stations within the Chiba array are used to estimate the ground strains. The ground displacements are obtained by the double fold integration of the acceleration records. The integration is performed in the frequency domain with the aid of the Fast Fourier Transform.

Band-pass filtering is carried out on the acceleration records in accordance to the characteristics of the acceleration transducers that are used for the array observation. Since the accelerometers have a practically flat sensitivity in the frequency range between 0.1 Hz and 30 Hz, the application of a band-pass type filter having a lower cut-off frequency of 0.1 Hz is unavoidable for any meaningful result.

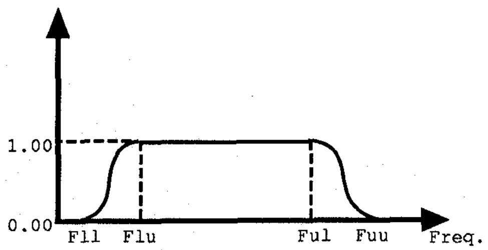


Fig. 4 Band-pass filter applied to the records

The band-pass type filter is shown in Fig. 4. Non-zero transition regions are in the forms of cosine functions to make the amplification factors to vary smoothly from the pass-band (F_{lu} and F_{ul}) to the stop-band (F_{ll} and F_{uu}) frequencies.

The average ground strain between two points is calculated from their ground displacements as follows:

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

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. Band-pass filtering of the evaluated strain is performed in order to minimize the effect of noise. The strain evaluation process is shown in Fig. 5.

The evaluated strains were compared to the strains measured directly by the ground strain transducers in order to investigate their accuracy. Previous studies by the present authors [9] have demonstrated the reliability of the strains measured by the transducers for the frequencies higher than 0.1 Hz.

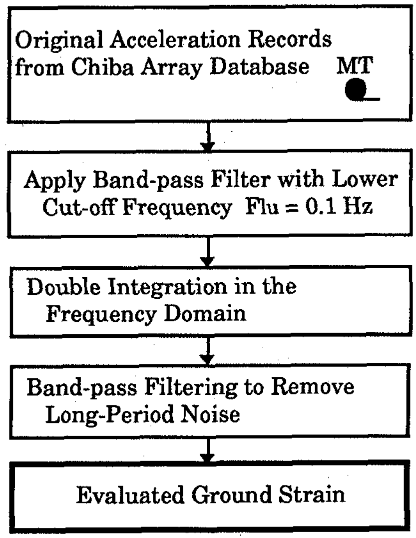
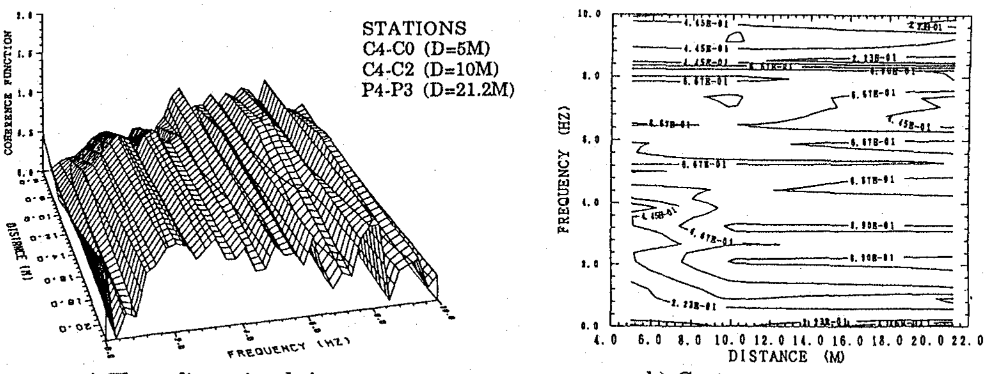


Fig. 5 Procedure for evaluation of ground strain

A comparative analysis in frequency domain was carried out with the aid of the coherence function, the phase delay, and the Fourier spectrum ratio. When estimating the spectra for a pair of records, a smoothing technique is employed with the Parzen window of bandwidth = 0.30 Hz.

Figure 6 shows a three-dimensional representation of the coherence function for the evaluated and the directly measured strains. The variation of the coherence function with the separation distance between stations is presented. The strains were evaluated in the direction of the transducer G3 for the event 8722. The corresponding contour map is also presented. A cut-off frequency of 0.1 Hz was adopted for the low-cut filtering of the evaluated strains.



a) Three-dimensional view b) Contour map

Fig. 6 Coherence function $coh^2(f,D)$ for evaluated and measured ground strains for the event 8722 in the direction of transducer G3

Good agreement between evaluated strains and directly measured strains was observed in the frequency range between about 1.0 Hz to 8.0 Hz. On the contrary, poor levels of correlation were found at the low range of frequencies (f<1.0 Hz). Figure 7 shows the power spectra of evaluated and directly measured strains for event 8722. A very strong amplification of the spectral amplitudes was observed at frequencies lower than 1.0 Hz for the evaluated ground strain and this amplification reached very high levels for the 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. 8. The separation distance D was kept constant at 21.2 m in all the cases. The cut-off frequency is 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 earth-

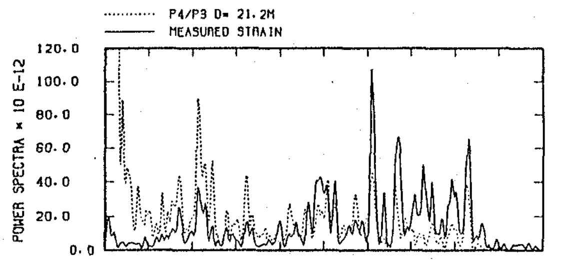


Fig. 7 Power spectra of evaluated and directly measured strains for event 8722

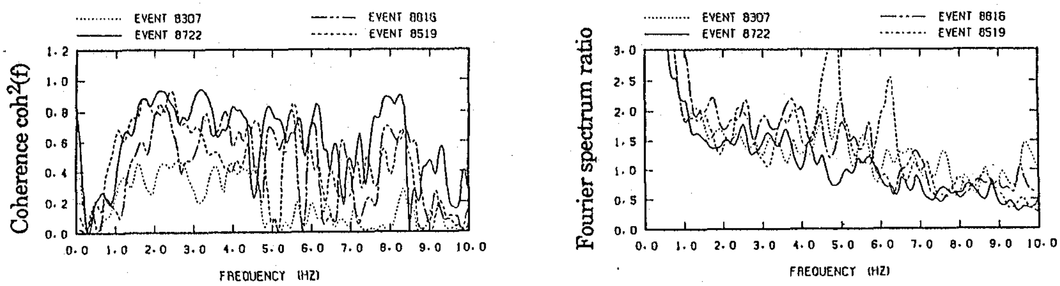


Fig. 8 Correlation between evaluated and measured ground strains for four events

quakes. However, the intensity of the motion was found not to be a decisive parameter on the level of correlation between evaluated and directly measured strains.

Important differences were found for the frequencies lower than 1.0 Hz where the amplification of the spectral amplitudes of the evaluated ground strain reached very high levels in all the cases.

It can be said from these observations that the accuracy of the strains evaluated from ground displacements is significantly dependent on the spacing between the two stations and that the low frequency range of the evaluated strains includes peaks that are not present in the case of the directly measured strains and which are likely to be the result of long-period noise.

4. EFFECT OF SEPARATION DISTANCE ON THE EVALUATION OF GROUND STRAINS

The ground displacements that were determined in two directions at nine boreholes of the Chiba array were employed to investigate the effect of the separation distance between two stations on the accuracy of the evaluated strains. Ordinary coordinates transformation was performed to determine the ground strains in the directions of the transducers G1 and G3. The data recorded during the four selected earthquakes were used in the analysis.

The effect of the spacing between stations on the evaluation of ground strains is presented in Fig. 9. The level of correlation between the evaluated strains and the directly measured strains is expressed in terms of the maximum strain ratio 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

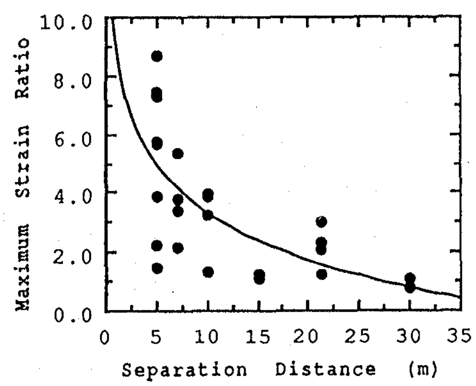


Fig. 9 Effect of the spacing between stations on the evaluation of ground strains

large. 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 to be more sensitive to noise due to the high noise-signal ratio. Note that, for short separation distances, the amplitude of the evaluated strain was found in some cases to be more than eight times the amplitude of the directly measured strain. A better agreement was observed for longer separation distances.

Logarithmic regression analysis was conducted employing the data of the four earthquakes in the directions of transducers G2 and G3. The following expression was derived:

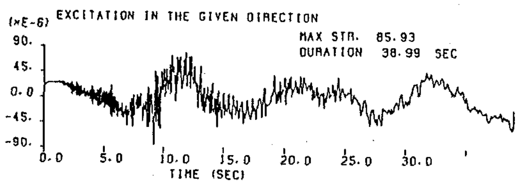
$$SR = 8.757 - 5.418 * \mathrm{Log}(D) \tag{2}$$

where SR is the maximum strain ratio and D is the separation distance between the two stations. This relationship is also shown in Fig. 9. According to this derived expression, the optimum spacing for the evaluation of the ground strain ranges from about 20 to 30 m. The difference in amplitude between the evaluated strain and the directly observed strain is less than 10 % within this spacing range.

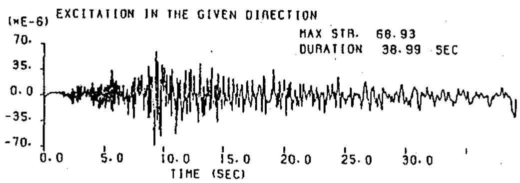
5. EFFECT OF LONG-PERIOD NOISE ON THE EVALUATION OF GROUND STRAINS

Figure 10 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.

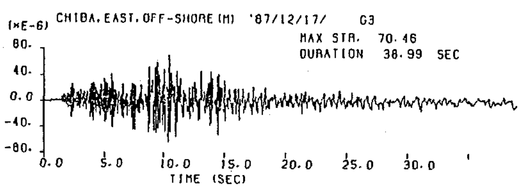
The effect of the application of various cut-off frequencies was studied to remove the long-period noise. The results obtained for the event 8722 in the direction of the transducer G3 are presented in Fig. 11. Various separation distances were considered as well. The level of agreement between evaluated strains and directly measured strains was expressed once again in terms of the maximum strain ratio.



a) Evaluated strain; Flu = 0.10 Hz



b) Evaluated strain; Flu = 0.40 Hz



c) Directly measured strain G3

Fig. 10 Time histories of ground strains evaluated for event 8722 using various low-cut filters

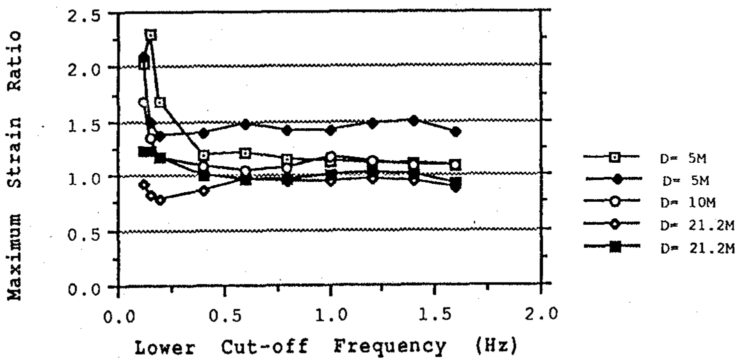


Fig. 11 Effect of the low-cut filtering on the evaluation of ground strain (Event 8722, direction of transducer G3)

It can be seen that while good agreement (SR=1.0) was easily obtained for the long separation distances (D>20 m) by cutting off the frequencies lower than about 0.4 Hz, little improvement could be achieved for the strains evaluated using short separation distances. It is also to be noticed the strong scatter observed for the low values of the cut-off frequency. The scatter diminishes for the larger cut-off frequency values.

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. These strains were employed to investigate the effect of the low-cut filtering on the evaluation of ground strains from displacement records.

The results of the analysis are presented in Fig. 12 together with the curve obtained by conducting a logarithmic regression analysis on the data. The following expression which relates the level of agreement between the evaluated strains and the directly measured strains to the cut-off frequency of the low-cut filter is derived.

$$SR = 0.9626 - 0.611 * \mathrm{Log}(F_{lu}) \tag{3}$$

where SR is the maximum strain ratio as defined previously, and F_{lu} is the lower cut-off frequency. It can be concluded that the frequencies lower than about 0.40 Hz are to be cut off in order to remove the long-period noise from the ground strains evaluated from the displacement records at two stations.

As an application of the results obtained in this investigation, strains were evaluated for the selected ground motions using the proposed optimum values of separation distance between the stations and cut-off frequency. Figure 13 shows the coincidence between evaluated strains and directly measured strains for events 8722 and 8816.