MEASUREMENT OF SEISMIC GROUND STRAIN BY A DENSE SEISMOGRAPH ARRAY

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SUMMARY

Based on the ground acceleration records obtained by a very densely located seismometer network, it is attempted to find a rational solution for calculation and analysis of ground strains. In the present study the effects of spacing between seismometers as well as depth are investigated. To find the accuracy of calculated strains the results are compared with the directly measured ground strains. It is shown that the calculated strains are in good agreement with directly measured ones.

INTRODUCTION

Without any doubt, the seismic behavior of the buried linear structures such as pipes and tunnels are strongly influenced by the relative displacement of the surrounding soil. Recently this concept has been incorporated for seismic resistant design of some lifeline systems embedded in the ground, but the observational data on the seismic soil strain has been limited and fragmentary so far and the quantitative information on the properties of engineering importance is extremely lacking.

A very densely located seismometer array consisting of 36 three-component accelerometers was completed and the simultaneous recording of 108 components of ground motions on and in the ground began in April, 1982. Using the earthquake ground motion records obtained by this system, it became practically possible to obtain the characteristics of soil strain during the occurrences of earthquakes in a comprehensive and reliable manner. Since December, 1982, the array network was expanded with a complementary system including direct measurement of relative ground displacements as well as observation of strains in a buried steel and ductile-cast-iron pipes, both of 150 mm in diameter and some 120 m in length.

In this paper, emphasis is placed on the following two points: (1) The effect of spacing between seismometers on the accuracy of calculated strains, and (2) The effect of depth on the magnitude of calculated strains.

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GENERAL LAYOUT OF OBSERVATION NETWORK

The Site

The observation network is located in the Chiba Experiment Station of the Institute of Industrial Science, the University of Tokyo. The topographical and geological conditions of the site are generally simple with the ground surface being almost flat. The superficial layer is loam with a thickness of 4-5 m resting on a 4-meter-thick clayey layer. The clayey layer is underlain by a sand layer. A typical soil profile obtained from one of the boreholes in which seismometers were installed is shown in Fig. 1.

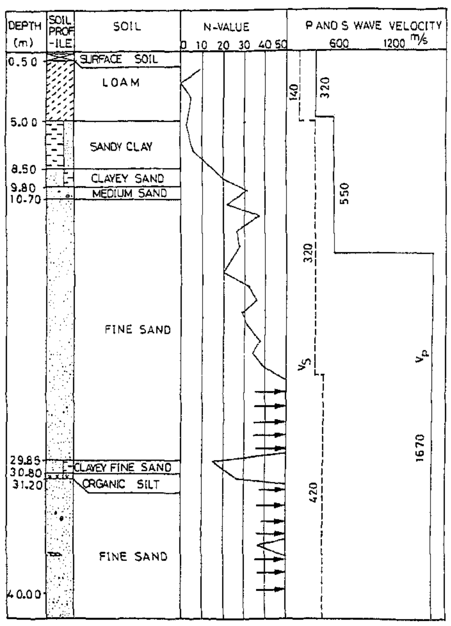


Fig. 1 Typical Soil Profile

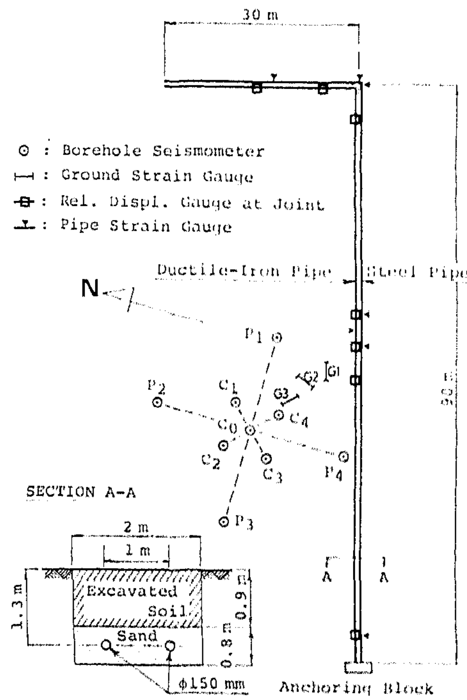


Fig. 2 Layout of Observation System

The Array and Direct Measurement System

Figure 2 shows the general layout of the array network as well as the newly developed direct strain measurement system. The latter system includes the direct measurement of uni-axial relative displacements in three different directions (G1, G2, and G3), and the strain measurements of a steel as well as a ductile-cast-iron buried pipe. This system is capable of simultaneous recording of 24 strain components.

The general configuration of the array network with a total number of 36 three-component accelerometers is shown in Fig. 3. There is a large triangular network C0-P5-P6 with the three sides having approximately 110 m in length. A cluster of eight points surrounds point C0, four of which are only 5 m and the rest are 15 m from C0.

The Instrumentations

The piezo-electric type acceleration transducer is used for the array observation. It is expected that the seismometers have a practically flat sensitivity in the frequency range between 0.1 Hz and 30 Hz.

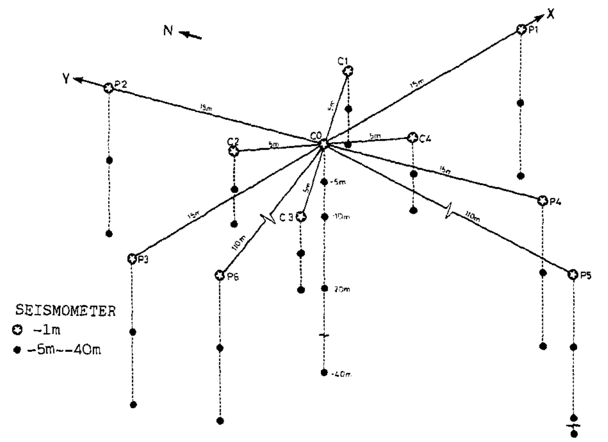


Fig. 3 General Configuration of Array Network

The signals from the seismometers are transmitted by cable, digitized by AD-converter with the time interval of 1/100 s, and recorded by two 64-channel digital recorders. From July, 1983, the digitizing time interval has been changed to 1/200 s. Timing information is internally generated, and in addition, the absolute time is corrected hourly by utilizing the signal from N.H.K. (the Japan Broadcating Corporation). The recording devices are activated when a trigger experiences motion above a preset threshold level. Besides, the recording system has a 1.5 s pre-event memory, which makes it possible to obtain the initial part of the ground motion often needed in these analyses. The overall explanation of the system has appeared elsewhere (Refs. 1 and 2).

METHOD OF ANALYSIS

Finite element method in three dimensional space has been employed to calculate the ground strains. A tetrahedron element with an assumed linear shape function constitutes the basic element.

From Fig. 3 it is evident that the combination of any four points which are not located in the same plane forms a tetrahedron element. This is one of the advantages of this system which makes it possible to evaluate the effect of different factors such as spacing between seismometers, depth, different regions, etc. on the calculated ground strains. In the following sections the effects of the first two factors are discussed in some detail.

Fast Fourier transform was applied throughout the analyses. In the present study all the integrations for calculation of velocities and displacements were performed in frequency domain.

SEISMIC-INDUCED GROUND STRAIN

30 earthquakes have been recorded as of October, 1983. In this paper only the results of one of the best records so far obtained during the earthquake of February 27, 1983, are discussed. Some other results have been treated elsewhere (Refs. 3-5). This event occurred in the southern part of Ibaragi Prefecture, with a magnitude of 6.3 on the Richter scale and an approximate epicentral distance of 40 Km. The maximum recorded acceleration

at the observation site was about 70 Gals.

A sample of calculated components of strains in the horizontal plane at a depth of approximately 1 m is shown in Fig. 4.

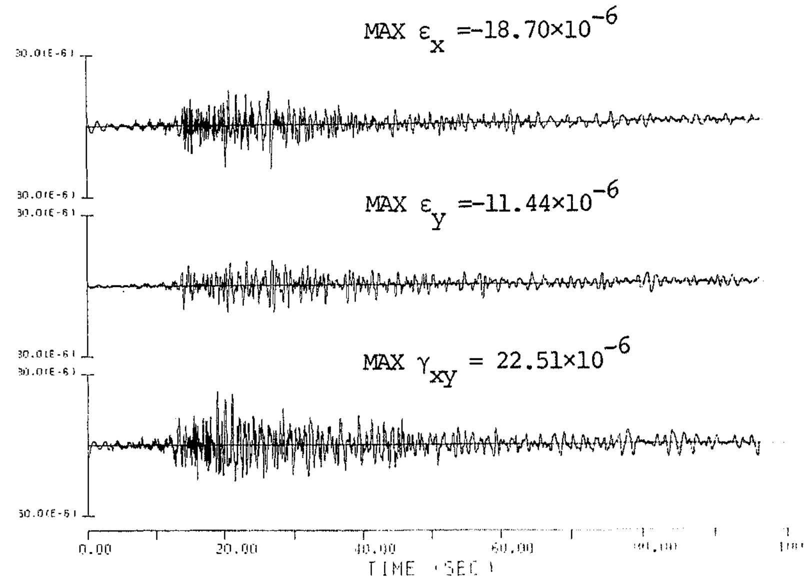


Fig. 4 Sample of Calculated Components of Strain
Element P1(-1m)P3(-1m)P5(-1m)P5(-40m)

A tetrahedron element with the vertices at P1(-1m), P3(-1m), P5(-1m), and P5(-40m) is used. For this particular event the maximum values of normal strains (ε_x and ε_y)and shear strain (γ_{xy}) are 19×10^{-6}, 11×10^{-6} and 23×10^{-6} respectively.

Effect of Spacing Between Seismometers

To investigate the effect of spacing between seismometers, three elements with the sides of approximately 110 m, 30 m, and 5 m were selected. These elements have vertices at points P1(-1m)P3(-1m)P5(-1m)P5(-40m), P1(-1m) P3(-1m)P4(-1m)C0(-40m) and C0(-1m)C3(-1m)C4(-1m)C0(-5m), respectively.

To judge the accuracy of calculated strains, they were evaluated in three specified directions, which coincide with the directions of directly measured relative ground displacements. A portion of enlarged strain time histories in G1 direction calculated in the aforementioned three elements are shown in Fig. 5. Figure 6 shows the same portion of time histories, all in G1 direction, of directly measured ground strain, steel pipe strain, and relative motion in a joint of ductile-cast-iron pipe.

Surprisingly the time histories as well as Fourier spectra of calculated strains show quite reasonable similarity with the actually observed ones.

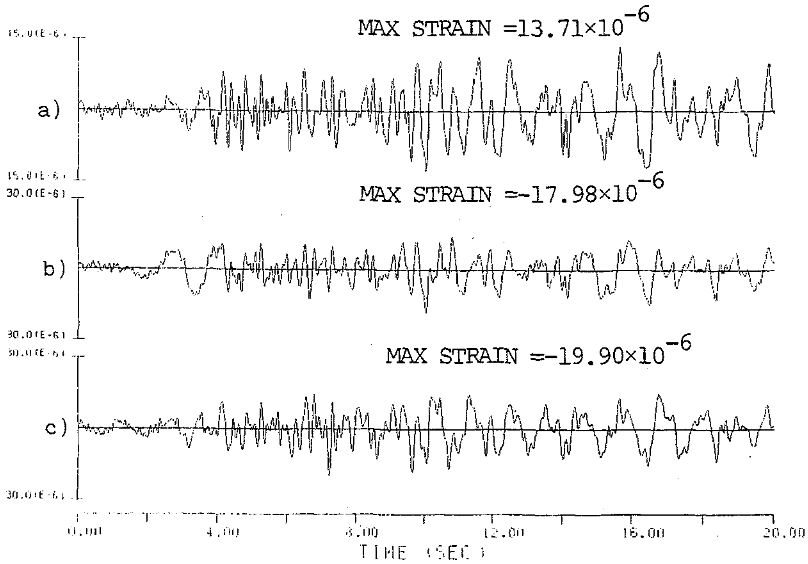


Fig. 5 Calculated Strain in G1 Direction
a) P1(-1m)P3(-1m)P5(-1m)P5(-40m)
b) P1(-1m)P3(-1m)P4(-1m)CO(-40m)
c) CO(-1m)C3(-1m)C4(-1m)CO(-5m)

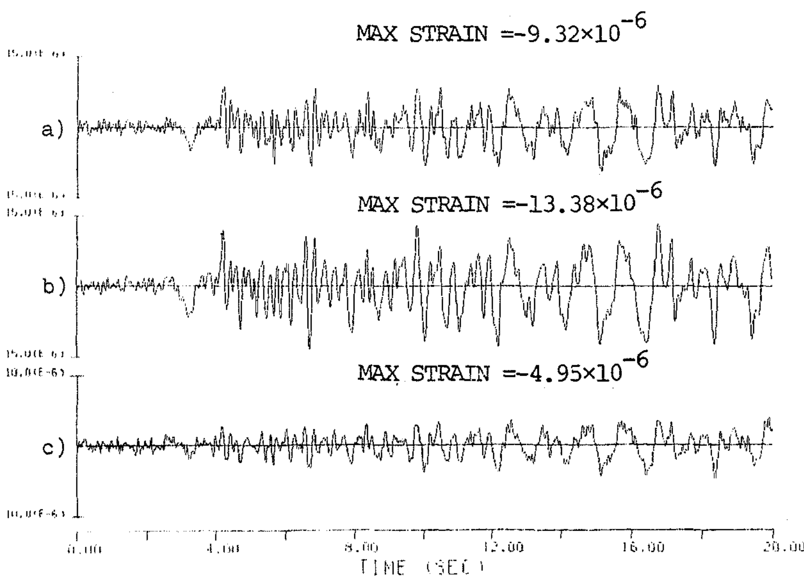


Fig. 6 Measured Strains in
a) Ground
b) Steel Pipe
c) Joint of Ductile Pipe

The order of strain in the largest element shows good agreement, but the calculated strain becomes somewhat larger in small elements especially in the element with the side of only 5 m. To intepret this problem two main reasons were speculated.

1. During the preliminary observations it was found that some of the seismometers seem to be out of the preset directions. This trouble has been discussed (Ref. 1) and the effect of out-of-preset direction of seismometers on the calculated strains was studied (Ref. 3). Although this problem has been greatly removed but existence of slight incorrect direction of seismometers has rather significant effect on the calculated strains over the short spans of only 5m.

2. Since in the calculation of strains relative values are involved, a slight difference between characteristics of individual seismometers has a great influence on the accuracy of the calculated strains, especially for very short spans. Also the existing integration methods for the calculation of ground displacements are known to be sensitive to various assumptions and parameters involved. This factor is also emphasized over shorter spans.

It is also interesting to note that, very roughly speaking, for smaller elements the higher frequency contents and for larger elements the lower frequency contents show the best agreement with the real strains. It was also revealed that the steel pipe experiences almost the same strain as that of the surrounding soil. Although the relative motions in joints of ductile pipe also show similar characteristics, their magnitudes are substantially smaller.

The predominant frequency content of ground strains for this particular event was found to be approximately 1 Hz, with the maximum strain of 9.5×10^{-6}.

Effect of Depth

Figure 7 shows the acceleration and displacement time histories of NS component at point P1 at the depths of 1 m, 10 m, and 20 m.

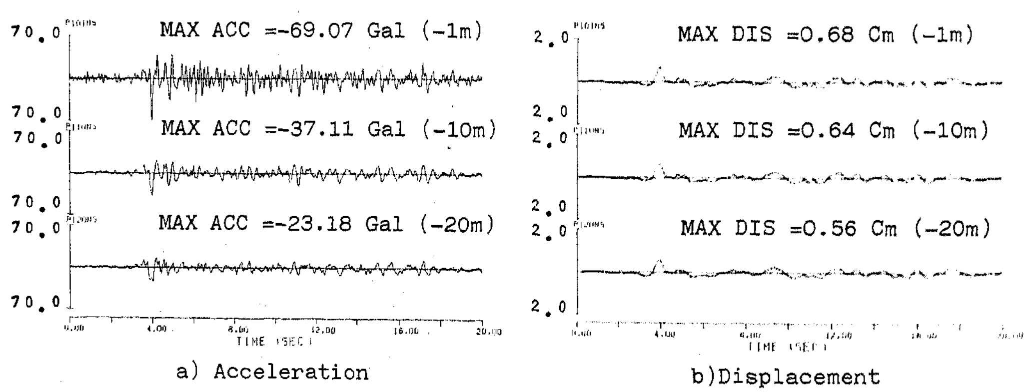
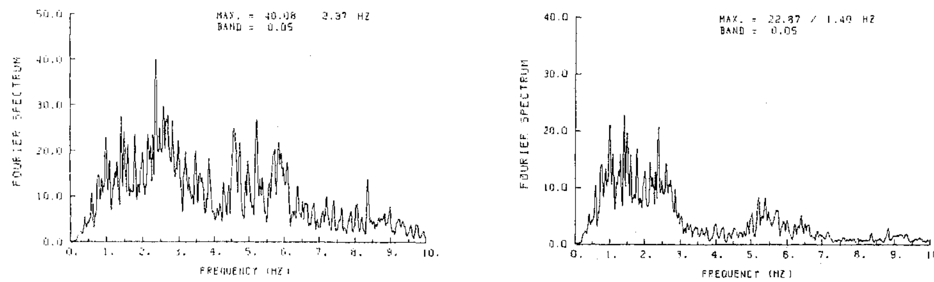


Fig. 7 Recorded Acceleration and Calculated Displacement at (-1m, -10m, and -20m)

The amplification effect of superficial subsoil on acceleration is clearly observed.



a) At the Depth of (-1m) b) At the Depth of (-20m)

Fig. 8 Acceleration Fourier Spectra
at (-1m and -20m)

Referring to Fig. 8 which shows the Fourier spectra of accelerations at depths of 1 m and 20 m, it is interesting to notice that the amplification effect seems to be emphasized in the higher frequency contents (more than 3.5 Hz). On the contrary, the amplification effect is not significant for ground displacement.

To investigate the effect of depth on the ground strain, elements of the aforementioned sizes were chosen so that for each element three of the vertices were located at the depth of 1 m, 10 m, and 20 m, respectively. Using the components of strain calculated in the largest element, the strains in the direction of G1 were obtained for the three different depths as shown in Fig. 9.

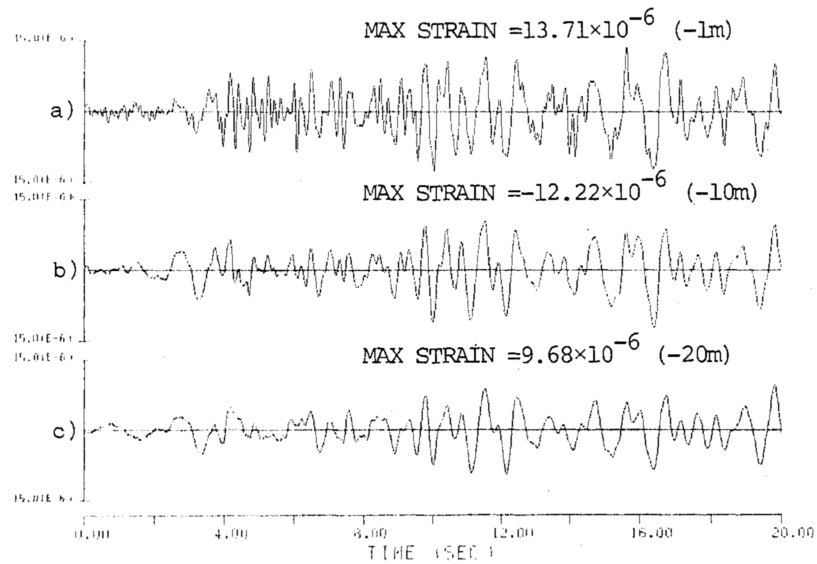


Fig. 9 Calculated Strain in G1 Direction
a) at the Depth of (-1m)
b) at the Depth of (-10m)
c) at the Depth of (-20m)

The amplitude of strains does not show significant reduction with depth, but the higher frequency contents are greatly suppressed in deeper layers.

CONCLUSIONS

In the present study an attempt was made to calculate the seismic-induced ground strains by the acceleration time histories obtained in a very densely located seismometer array network. Emphasis was mainly laid on the effect of spacing between seismometers as well as depth on the calculated ground strain. The strains were evaluated in a rather large, intermediate and small tetrahedron elements. Comparison with the directly measured ground strains revealed that the calculated strains in the element with the side of approximately 110 m show the best agreement, while agreement was poorer for the smaller element.

The amplitude of calculated strains at deeper layers (up to 20 m) do not show significant reduction with depth but the higher frequency contents are greatly suppressed.

The observed strains in the joints of ductile-cast-iron and steel pipes generally show very similar characteristics compared with those of the surrounding ground but for ductile pipe the magnitude is smaller.

ACKNOWLEDGMENTS

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