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STRAIN DEPENDENCE OF SOIL PROPERTIES INFERRED FROM THE STRONG MOTION ACCELEROGRAMS RECORDED BY A VERTICAL ARRAY

Yoshiyuki NOZAWA[1], Haruo OHKI[2] and Tadashi ANNAKA[2]

[1]Eng. research center, Tokyo Electric Power Co., Inc.,
2-4-1, Nishi-Tsutsujigaoka, Chofu-shi, Tokyo, Japan
[2]Seismic Eng. Dept., Tokyo Electric Power Services Co., Ltd.,
1-3-1, uchisaiwai-cho, Chiyoda-ku, Tokyo, Japan

SUMMARY

Strong motion accelerograms, whose peak horizontal ground acceleration exceeded 400 gal, were recorded by a vertical array. However some portions of the records suffered from saturation. These records were interpolated in order to investigate the strain dependence of the soil properties. The strain dependence of the soil shear moduli is well recognized and it agrees with the result from the equivalent linear procedure when the effective strain is about 0.3 times as much as the maximum strain. The strain dependence of the damping isn't obvious and it is very small compared with the result from the ordinary equivalent linear procedure.

INTRODUCTION

Until now strong motion accelerograms recorded by a vertical array are rare, while these motions are needed to examine the strain dependence of the soil properties. Fortunately during the eastern Yamanashi earthquake of August 8, 1983 the strong motion accelerograms were recorded by a vertical array at a substation (SFJ) of TEPCO in Shizuoka prefecture, Japan. However some of these records suffered from saturation. In order to investigate the soil properties during strong motions, these records were interpolated.

In the present study the authors examined the following things: (1) the methods of interpolation, (2) the frequency dependence of the damping constant Q while receiving small acceleration and (3) the strain dependence of the soil properties during the strong motions mentioned above.

OBSERVED RECORDS

Figure 1 shows the original accelerograms, after A/D conversion, recorded by a vertical array of SFJ during the eastern Yamanashi earthquake of August 8, 1983 (epicentral distance = 18Km, magnitude = 6.0, focal depth = 22Km). The amplitudes decreased to one third after the automatic gain control (AGC) system activated. The activation time of AGC system is indicated by the solid line crossing accelerograms in Figure 1. From now on the observed records mean the records which were corrected for AGC, while the original records mean non-corrected records. In Figure 2 the solid lines express the observed records. Figure 2 shows that the observed records suffered from saturation and have unusual spikes. The saturated portions and unusual spikes are indicated by open circles and triangles,

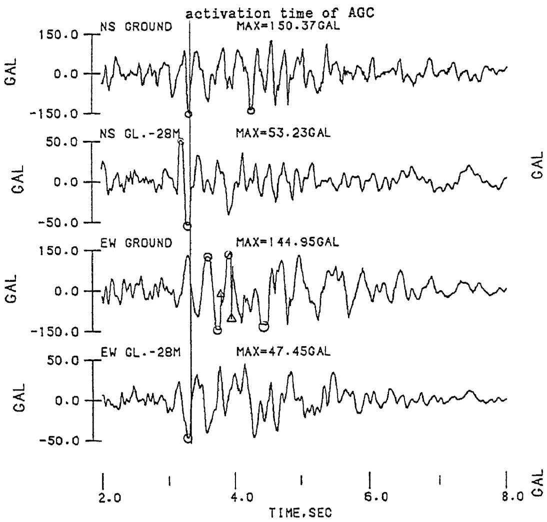

Fig.1 Original A/D converted records at SFJ in August 8, 1983 : The open circles and triangles denote the saturated portions and the two unusual spikes, respectively.

respectively in Figure 1. The two unusual spikes only exist on the EW component of the record at the ground surface. Both the saturated portions and the spikes are supposed to be wrong data.

INTERPOLATION OF RECORDS

Two methods of interpolation of the records were used. One uses a polynomial expression and the other uses trigonometric functions. Figure 2 shows the observed records comparing with those interpolated by both methods. Excepting EW component of the ground surface motion there is not so much difference between the two methods for the interpolation.

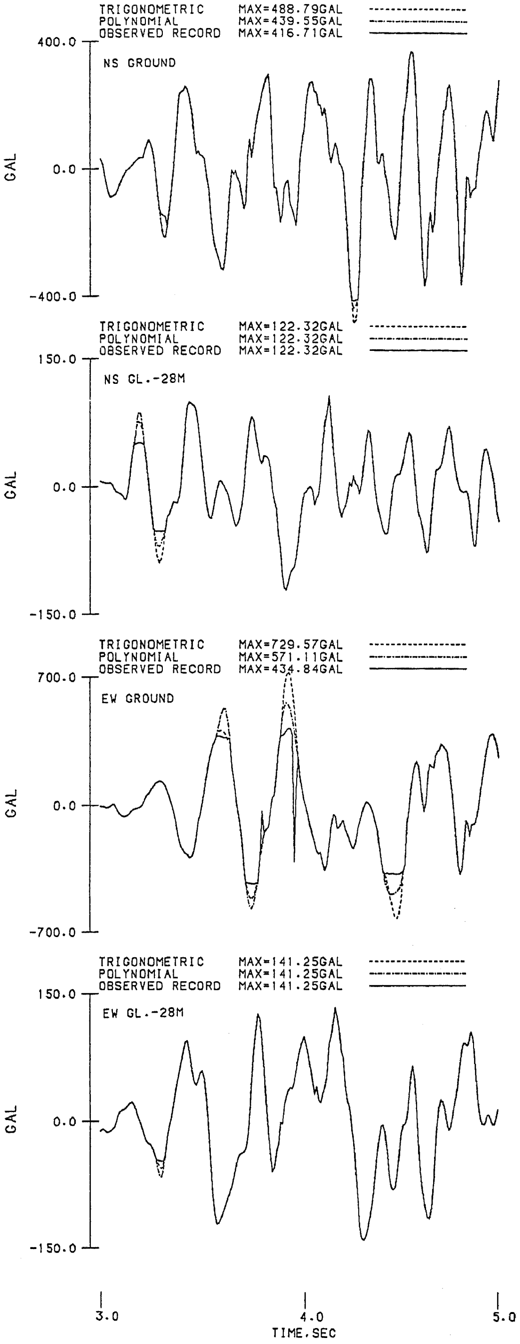

Fig.2 Comparisons of the observed time histories and interpolated time histories.

The Case of Using Polynomial Expression

In order to interpolate the records, one cycle of the recorded data which include the unknown portions such as the saturated portions are selected at first. One cycle contains about 30 to 40 data. Using the least square method, the polynomial expression which fits best to the known data is determined. While the degree of fitness of the known portions increases with the higher order term of the polynomial expression, the unknown portions tend to become more unnatural. Being compared the shapes of the interpolated records, the eleventh order polynomial expression is adopted and the results are shown in Figure 2.

The Case of Using Trigonometric Functions Picking up a series of 200 data (3.0-5.0 sec.) which includes the unknown portions, the authors tried to express it by using trigonometric functions, i.e. a kind of discrete Fourier transform, as follows;

$$A(t)=b_0+\sum_{n=1}^{M}\{a_n\sin(2\pi\cdot n\cdot\Delta f\cdot t)+b_n\cos(2\pi\cdot n\cdot\Delta f\cdot t)\}$$

where A(t) is the expression for interpolation, a_n and b_n are the coefficients of Fourier series, Δf is the frequency interval for the calculation which is determined by the length of the data used, t is the time and $M\Delta f$ is equal to the highest frequency used. The coefficients a_n and b_n should be decided using the known data. Also in this case, while the degree of fitness of the known portions increases with the higher order frequency of the trigonometric function—i.e. with the lager number M, the unknown portions tend to become more unnatural. In Figure 2 the used highest frequency of the trigonometric function is 15 Hz excluding EW component of the record at the ground surface. By this frequency range, the authors could not interpolate EW component successfully. As a result the highest frequency of 10 Hz was used for the EW component.

Comparing Two Methods of Interpolation

Figure 3 shows the spectral ratios of both the observed records and the interpolated records. The spectral ratios were calculated from the data between 3.0 and 20.0 seconds. The influence of the interpolation on the spectral ratios is not so large. The records interpolated by the polynomial were used for the subsequent analysis. In the case of using the records interpolated by the trigonometric, the results mentioned below are almost the same. The records were corrected for the direction error occurred in setting the seismometers. This has been estimated by the difference between the orbits of the ground surface motion and those of the underground, using the frequencies lower than 1 Hz. (Ref. 4)

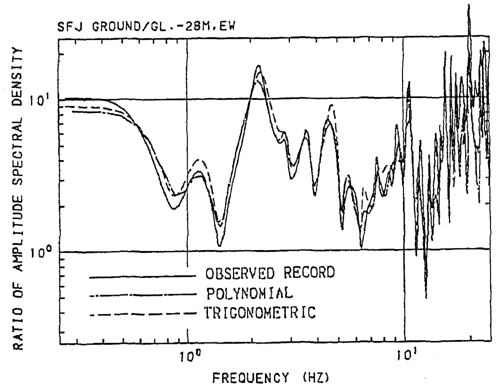

Fig.3 Spectral ratios of the observed records and the interpolated records.

FREQUENCY DEPENDENCE OF SOIL DAMPING DURING SMALL EARTHQUAKE

At substations of TEPCO in Tokyo many ground motion accelerograms which are not so strong are recorded by vertical arrays. In the left figure of Figure 4 the average of the spectral ratio of the observed records at a substation and those of one standard deviation from the average are compared with those calculated by one dimensional wave propagation theory. This left figure shows that the peak frequencies of the spectral ratio are close to each other, but the peak spectral amplitudes are different. These values of the observed records are lower than those calculated in the range of lower frequency, while in the higher frequency rage those observed are higher than those calculated. Based on the recent researches (Refs. 1, 2), the authors supposed that this is caused by the assumption of constant damping with frequency in the calculation of the theory. In order to let the damping increase in the lower frequency range, the authors assumed that the damping constant Q is equal to 4f, where f is frequency. However based on the Ref. 1, in the range lower than 1 Hz, Q is assumed to be constant.

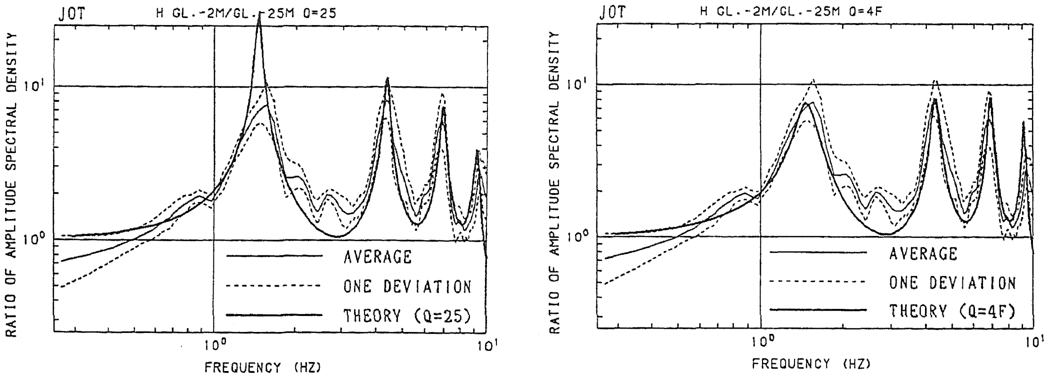

Fig.4 An example of comparison between the spectral ratio of the records observed during small acceleration earthquakes and transfer function by one dimensional wave propagation theory at a substation. The damping constant is equal to 25 in the left figure and 4f in the right figure.

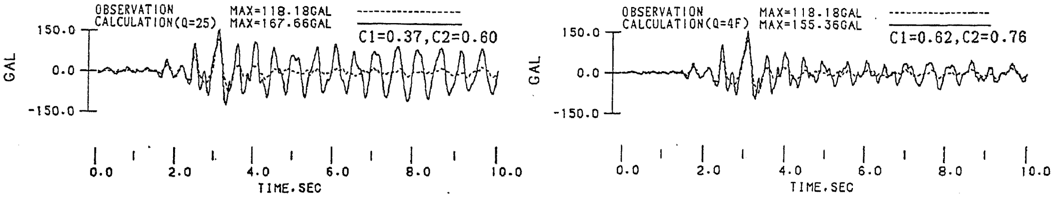

Fig.5 An example of comparisons between the calculated and observed time histories on the ground at a substation. The damping constant is equal to 25 in the left figure and 4f in the right figure.

The right figures of Figure 4 and 5 show the spectral ratios and the time histories of that case, i.e. the case of considering the frequency dependence of the damping, respectively. In Figure 5 the ground motion of the observed records is compared with that calculated by the theory using the records observed at the underground as input. And in this figure C1 is the cross correlation coefficient and C2 the ratio of RMS acceleration. This is the same for other figures. As shown in Figures 4 and 5, by taking into account the frequency dependence of the damping, the agreement becomes fairly good at least in the range of 1 to 10 Hz.

STRAIN DEPENDENCE OF SOIL PROPERTIES

Strain Dependence of Shear Modulus The strongest accelerograms recorded by vertical arrays of TEPCO are the records of August 8, 1983 at a substation SFJ mentioned above. The profile of S-wave velocities and the positions of the seismometers at SFJ are shown in Table 1. Figure 6 shows the spectral ratios of the ground motions to the underground motions of these records. In this figure the spectral ratio of The earthquake of August 8, 1983 is compared with those of other 5 earthquakes whose maximum accelerations are from 11 to 73 gal. The peak frequencies of EW component of August 8 earthquake are clearly different from those of other earthquakes. Such discrepancy is the same for NS component. This indicates the strain dependence of the shear modulus of the soil.

Table 1 Profile of S-Wave Velocities at SFJ

Depth (m)	S-Wave Velocity (m/S)	Position of Seismometer
0.0~	135	▲Ground
5.0~	145	
7.0~	230	
13.2~	320	
24.0~	700	
28.0~	621	▲GL.-28.0m

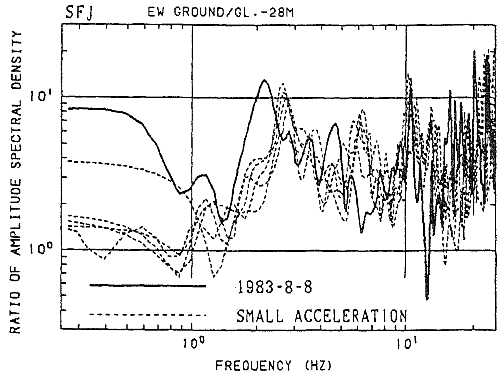

Fig.6 Spectral ratios of the records observed at SFJ.

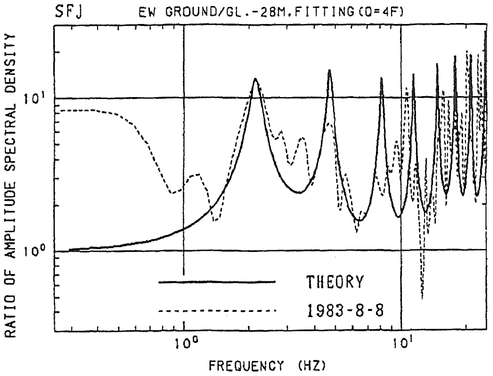

Fig.7 Spectral ratios of the record observed at SFJ in August 8, 1983 and fitting transfer function by one dimensional wave propagation theory.

<u>Linear Procedure Using The Decreased Shear Modulus and Q=4f</u> When the shear moduli of every layers are assumed to be decreased at a constant ratio, the shear modulus needs to be decreased to 55% from the values in Table 1 on EW component and to 85% on NS component, in order to explain the shift of peak frequencies in the spectral ratio caused by August 8 earthquake. In Figure 7 the spectral ratios of the observed records are compared with those of the results calculated by one dimensional wave propagation theory with the linear procedure under the condition that the shear moduli were decreased as mentioned above and that the damping constant Q of the soil is equal to 4f. Figure 8 shows the time histories in the same case as Figure 7. These figures show that the results of the calculations fit the observations well. Though this method is good for the simulation, it can't be used for the aseismic design, because we can't predict how much the shear modulus decrease during an earthquake.

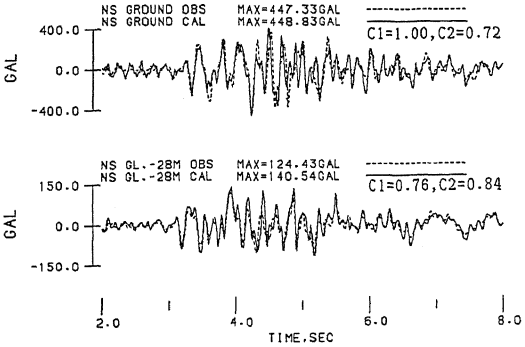

Fig.8 Comparisons between the time histories calculated using transfer function of one dimensional wave propagation theory, which is shown in Fig.7, and the time histories observed at SFJ in August 8, 1983.

<u>Equivalent Linear Procedure</u> For the purpose of considering the strain dependence of the shear modulus and the damping, the equivalent linear procedure is applied to one dimensional wave propagation theory in the case of the analysis for strong motions. The strain dependence of those used in the calculation is determined based on the laboratory tests. The strain dependence of the soil properties is assumed to be concerned with the effective strain which is 0.65 times as much as the maximum strain. But the results from this method don't fit to the observation well. Especially it is not good when the underground motions are calculated by using the observed surface ground motions as input. In this case the amplitudes of the calculation are larger than those of the observation. This was caused by the large damping in the high frequencies, which was estimated too large in the calculation for the strain dependence during the strong motions. When the frequency dependence of the damping was considered, the results are improved. In this case the frequency dependence of the damping is expressed as follows:

$$Q(f)=(f/6.25)Q(6.25) \quad (f > 1\ \text{Hz})$$
$$Q(f)=\text{const.} \quad (f < 1\ \text{Hz})$$

This procedure was derived from the assumption that Q(6.25) is equal to the results of the laboratory tests on the soil damping. 6.25 Hz is the point where the value of the expression Q=4f coincides that of Q=25, which is a usual value for the small strain range. But these results are not better than those shown in Figure 8. It is necessary for improving the results of the simulation to evaluate both the damping and the effective strain smaller. Figure 9 shows the results calculated under the conditions that the damping is fixed at the expression Q=4f and does not depend on the strain, and that the effective strain is 0.3 times as much as the maximum strain. This figure shows that the agreements are well as much as those shown in Figure 8.

As shown in Figure 9, since the time histories calculated by the interpolated ground surface records as input are not so much different from the observed underground time histories which have less saturated portions, the methods of interpolation used in this paper are considered to be useful.

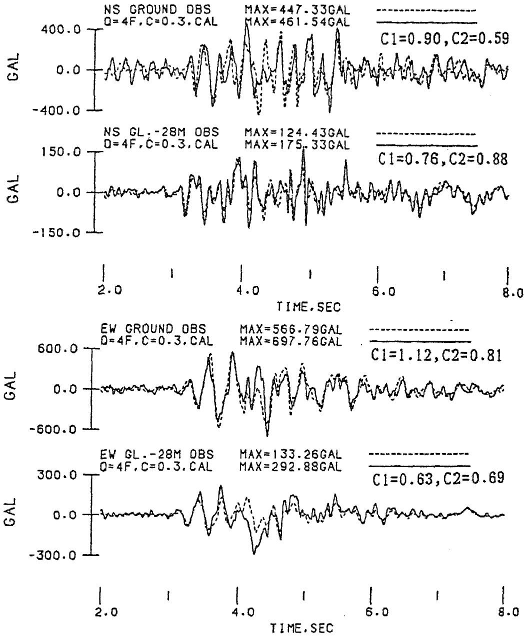

Fig.9 Comparisons between the time histories calculated using the equivalent linear procedure where the effective strain is 0.3 times as much as the maximum strain and the time histories observed at SFJ in August 8, 1983.

CONCLUSIONS

Based on the results obtained from the strong motion accelerograms of the earthquake of August 8, 1983, the following conclusions are obtained;

(1)the decrease of the shear moduli is clear as compared with the other earthquake records with smaller acceleration

(2)the increase of the damping ratio is not obvious in the larger strain range

(3)the decrease of the shear moduli is explained by assuming that the effective strain is about 0.3 times as much as the maximum strain in the equivalent linear procedure

(4)the frequency dependence and the strain independence of the damping constant Q should be taken into account for one dimensional wave propagation theory

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