# Dynamic soil properties obtained from strong motion records

## Les propriétés dynamiques des sols obtenues à partir des enregistrements de forts déplacements

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SYNOPSIS An analytical method is presented for estimating strain-dependent shear moduli and damping factors from strong motion accelerograms obtained only at the ground surface. The method is applied to four sites where the soil profiles are relatively simple and where several strong motion records are available. The computed shear moduli and damping factors are compared with laboratory test results including those for samples obtained from one of the sites. It was shown that: (1) the predominant period and the shape of Fourier spectrum of the observed motions reflect nonlinear properties of surface soil; (2) the computed relation of shear modulus and damping factor with shear strain is in good agreement with that obtained in the laboratory; and (3) the shear strain developed in the surface layer is well correlated with normalized peak ground velocity, based on which the degree of nonlinearity of the surface soil can be estimated.

## INTRODUCTION

The need for determining the actual properties of in situ soil during earthquakes has been emphasized, because strain-dependent properties of soil have a significant influence on the evaluation of ground response. For low shear strain of about $10^{-6}$, both shear moduli and damping factors measured in the laboratory have often been compared with those measured in situ. However, it still seems unclear whether the laboratory data could duplicate soil behavior in situ up to relatively large shear strains prevailing during strong earthquakes.

The object of this paper is to present analytical methods to estimate strain-dependent shear modulus and damping factor from strong motion accelerograms obtained at the ground surface, and to demonstrate the effectiveness of the method by comparing its result with that observed in the laboratory. Based on the analytical results, a possible factor to estimate the degree of nonlinearity of the surface soil is discussed.

## ANALYTICAL PROCEDURE

Abdel-Ghaffar and Scott (1979) estimated the shear modulus and damping factor of an earth dam on the basis of the shear beam analysis on strong motion records simultaneously recorded at the crest and the abutment. Similar studies on level ground, however, have not come to the authors' notice probably because of the unavailability of the strong motion accelerograms obtained at more than two depths at a site. Described hereafter together with Fig. 1 is a method of analysis using strong motion accelerograms obtained only at the ground surface.

### Shear Modulus

As shown in Fig. 1(a), the soil profile is modeled as a one-dimensional configuration composed of two horizontal layers, one of which is the surface layer with a finite thickness of H and the other the bedrock with an infinite thickness. Each layer is characterized by shear wave velocity, $V_s$, damping factor, h, and mass density, $\rho$ .

Assuming that earthquake ground surface motions are mainly due to the horizontal shear wave propagating from the underlying bedrock, and that the first predominant period, T, of the observed ground surface motion reflects dynamic characteristics of the surface soil, the average shear wave velocity of the surface layer can be given by

$$V_s = 4H/T \qquad (1)$$

The average shear modulus of the surface soil, G, becomes

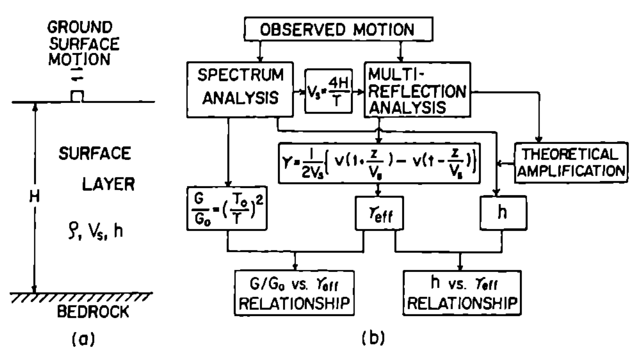


Fig. 1 Schamatic diagram of the proposed analyses

$$G = 16\ \rho(H/T)^2 \qquad (2)$$

Letting $T_o$ be the predominant period at $10^{-6}$ shear strain, Eq. (2) can be rewritten in the following form:

$$G/G_o = (T_o/T)^2 \qquad (3)$$

Eq. (3) indicates that the increase in the predominant period of the surface layer corresponds directly to the reduction in shear modulus ratio.

Shear Strain

Assuming that f(t) and g(t) are the particle velocities of the upward and downward shear waves at the top of a soil layer, shear strain, $\gamma$, at a depth of z from the top of the layer can be given by

$$\gamma(t,z) = [f(t+z/V_s)+g(t-z/V_s)]/V_s \qquad (4)$$

in which t is time and $V_s$ is the shear wave velocity determined by Eq. (1).

Considering the boundary conditions at ground surface leads to the following equation:

$$v(t) = 2f(t) = -2g(t) \qquad (5)$$

in which v(t) is the particle velocity at the ground surface, which can readily be obtained by integrating strong motion accelerogram at the ground surface. Thus the shear strain developed at any depth in the surface layer at any time can be given by

$$\gamma(t,z) = [v(t+z/V_s)-v(t-z/V_s)]/2V_s \qquad (6)$$

from which the maximum shear strain at any depth, $\gamma_{max}$, can be determined. It is reasonable to consider that an effective shear strain, $\gamma_{eff}$, corresponding to the shear modulus determined by Eq. (2) is less than an average of the maximum shear strains within the surface layer, $(\gamma_{max})_{ave}$. This is analogous to the concept in the equivalent linear analysis proposed by Schnabel et al. (1972). Thus, the effective shear strain is approximately given by

$$\gamma_{eff} = a(\gamma_{max})_{ave} \qquad (7)$$

in which a is assumed to be 0.65 for a whole time history of an accelerogram, and 0.85 for a duration of 10 seconds.

Damping Factor

Since the amplitudes of Fourier acceleration spectrum of the incident waves from the bedrock are approximately constant with period, Fourier acceleration spectrum at the ground surface is similar in shape to the amplification spectrum of the surface layer. The amplification spectrum is a function of the shear wave velocities of both surface layer and bedrock, and the damping factor of the surface layer. Thus by knowing the bedrock velocity in addition to the surface velocity from Eq. (1), the damping factor of the surface layer can be determined by a trial-and-error procedure. The effective shear strain corresponding to the damping factor thus obtained can be given by Eq. (7).

Limit of Applicability

Based on the proposed method, strain-dependent properties of surface soil may be evaluated for a site where several earthquake records are available and where the soil profile is relatively simple. However, for obtaining meaningful results, the following conditions must be satisfied.

In the evaluation of shear modulus and shear strain, the impedance ratio between surface layer and bedrock should be reasonably high, say greater than about 3. Under such a condition, the predominant period of the ground surface motion would correspond to that of the surface layer.

In the evaluation of damping factors, the impedance ratio should be greater than about 10. Under such a condition, the amplification characteristics of the surface layer would dominate the spectrum shape of the ground surface motions.

NONLINEAR SOIL PROPERTIES ESTIMATED FROM ACCELEROGRAMS

Based on the proposed method, nonlinear soil properties were evaluated for the following four sites: Shiogama Harbor, Hososhima Harbor, Hiroo Town Office, and Kushiro Japan Meteorological Agency (JMA) Observatory. The soil profiles of the four sites are shown in Fig. 2. Clayey soils dominate in the surface layers of both Shiogama and Hososhima sites, and sandy soils at Hiroo site. The surface layers at Kushiro JMA site are alternation of sand and clay strata. Site characteristics and number of accelerograms used for analyses are summarized in Table I. Strain-dependent soil properties were determined for a larger horizontal component of each set of accelerograms.

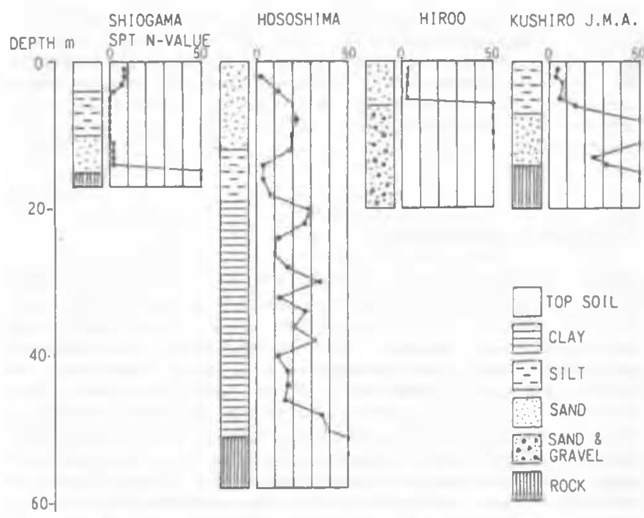


Fig. 2 Soil profiles of four sites used for analyses

Table I Site characteristics and strong motion records used for analyses

| Site | Soil | Depth (m) | $T_o$ (s) | ρ ($t/m^3$) | $V_{so}$ (m/s) | $V_{sb}$ (m/s) | No. of Acc. Records |
|---|---|---|---|---|---|---|---|
| Shiogama | Silt | 15 | 0.58 | 1.50 | 103 | 850 | 5 |
| Hososhima | Sand-Clay | 51 | 0.76 | 1.80 | 268 | 700* | 6 |
| Hiroo | Sand | 6 | 0.17 | 1.80 | 141 | 400* | 6 |
| Kushiro | Silt-Sand | 14 | 0.26 | 1.75 | 215 | >400* | 7 |

*Estimated value

Fig. 3 shows Fourier spectra of the records at Shiogama Harbor. Considering the first predominant period calculated from Eq. (1) using the shear wave velocity of the surface layer listed in Table I, the predominant periods of the observed motions appear to reflect the properties of the surface layer. The distinct trend in which the predominant period increases and the spectrum peak becomes less sharp with increasing amplitude of acceleration, characterizes nonlinear soil properties.

The relationship between shear modulus ratio and effective shear strain for the four sites are summarized in Fig. 4. Solid symbols in the figure are for clayey soils and open symbols for sandy soils. There is a fairly well-defined trend in which the shear modulus ratio decreases with increasing shear strain.

Fig. 5 summarizes the relation between shear modulus and shear strain for Shiogama site. Large symbols correspond to that for a whole record, and small symbols for a duration of 10 seconds. There is no significant difference in trend between the two symbols.

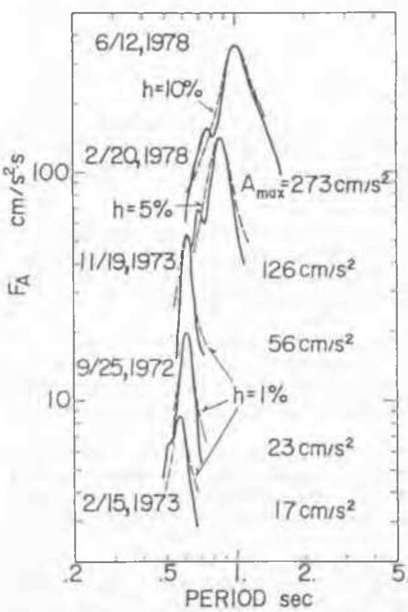


Fig. 3 Variation of spectra of strong motion records with acceleration amplitude

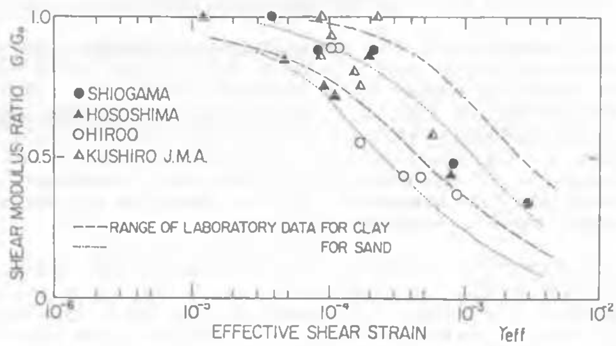


Fig. 4 Relationship between shear modulus ratio and shear strain

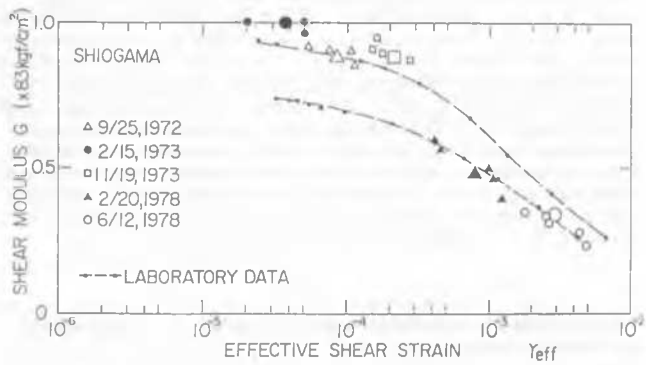


Fig. 5 Relationship between shear modulus and shear strain for Shiogama site

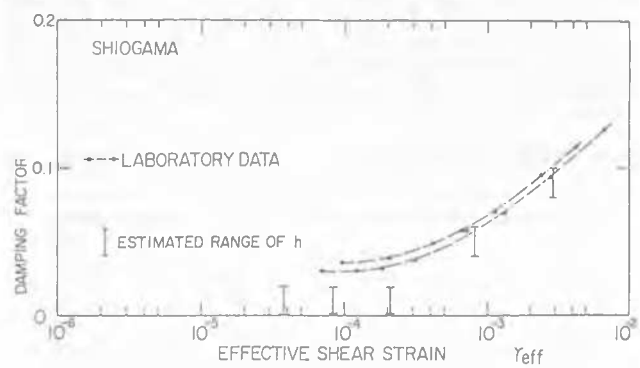


Fig. 6 Relationship between damping factor and shear strain for Shiogama site

An attempt was made to estimate damping factors at Shiogama site, since its high impedance ratio satisfies the requirement for the damping evaluation as described previously, and the shear wave velocity of the bedrock was known to be 850 m/s. The computed results are shown in Fig. 6 against shear strain. The damping factor for shear strains less than $10^{-4}$ is about 1 %, then increases gradually with shear strain, and becomes 10 % at a shear strain of about $3x10^{-3}$.

COMPARISON WITH LABORATORY TEST RESULTS

For comparison, the relationships between shear modulus ratio and shear strain from previous studies by other investigators (Kokusho, 1987) are shown in Fig. 4. As far as the normalized shear modulus ratio is concerned, the laboratory result is consistent with the actual field behavior. However, this does not necessarily indicate the agreement in the absolute values of shear moduli between the two.

In order to clarify the abovementioned issue, silty soils at depths from 5 to 10 m were sampled at the Shiogama site, and dynamic triaxial tests were run to determine their dynamic properties. The effective confining pressure of each test specimen was set equal to its vertical effective stress in situ.

The laboratory test results are shown in Figs. 5 and 6 for comparison. It appears that the analytical results are reasonably consistent with the laboratory data. It has been pointed out that laboratory and in situ shear moduli may differ significantly (Yoshimi et al, 1977), and that such difference increases as the soil becomes stiffer (Yasuda and Yamaguchi, 1984). The agreement between the analytical results and laboratory data, however, suggests that laboratory tests on soft silt carefully sampled can simulate its dynamic behavior in situ.

RELATIONSHIP BETWEEN SHEAR STRAIN AND INTENSITY OF GROUND MOTION

Fig. 7 shows the relationship between shear strain amplitude and normalized peak ground velocity. The normalized peak ground velocity is defined as a ratio between peak ground velocity and shear wave velocity of the surface layer at low strain level. It is clearly observed that the data lie within a narrow band regardless of the geological conditions at the sites.

For shear strains below $3x10^{-4}$, the data lie near the straight line with a slope of 1 to 1, indicating that the normalized peak ground velocity is directly proportional to shear strain. Above $3x10^{-4}$ strain, however, most of the data appear to lie below the line, probably reflecting the significant nonlinearity of the surface soil.

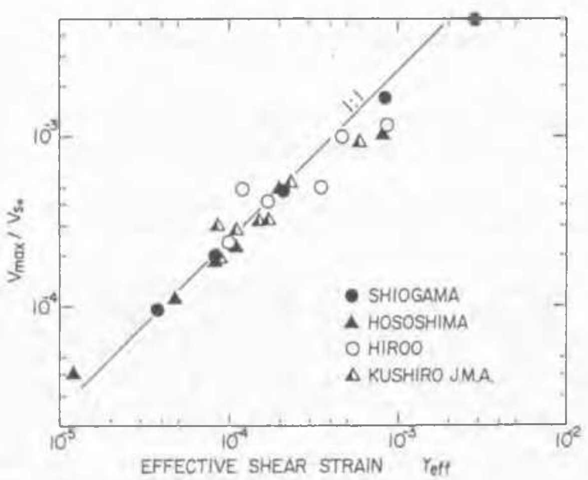


Fig. 7 Relationship between normalized peak ground velocity and shear strain

The well-defined correlation suggests that the degree of nonlinearity of surface soil can be estimated based on the normalized peak ground velocity. For example, a normalized peak ground velocity of $2x10^{-3}$ would indicate a shear strain of about $10^{-3}$ from Fig. 7, which corresponds to a shear modulus ratio of about 0.5 from Fig. 4.

CONCLUSIONS

On the basis of the analytical and experimental studies, the following conclusions may be drawn:

(1) An analytical method is presented for estimating strain-dependent shear moduli and damping factors from strong motion accelerograms obtained only at the ground surface.

(2) The fact that the predominant period increases and the peak of Fourier spectrum becomes less sharp with increasing acceleration indicates nonlinear properties of surface soil.

(3) The computed values of shear modulus and damping factor are in good agreement with the laboratory test results.

(4) The shear strain developed in the surface layer is well correlated with the normalized peak ground velocity, based on which the degree of nonlinearity of the surface soil can be estimated.

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