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Nonlinear Soil Properties Estimated from Strong Motion Accelerograms

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SYNOPSIS A rational procedure is developed for estimating dynamic soil properties from strong motion accelerograms obtained only at the ground surface. The method consisting of spectrum analysis and multi-reflection analysis could permit evaluation of time histories of shear modulus versus shear strain in the soil during an earthquake. The method is applied to four sites where the soil profile is relatively simple and where several strong motion records are available. The analytical results show that (1) the first predominant period of surface soil increases with an increase in shear strain developed in the soil, (2) the strain-dependent shear moduli evaluated from strong motion records are in fairly good agreement with laboratory test results in a strain range from 10^{-5} to 10^{-3}, and (3) the shear modulus ratio is better correlated with peak particle velocity at the ground surface than with peak acceleration.

INTRODUCTION

The need for clarifying the actual properties of in situ soil during earthquakes has been emphasized, because strain-dependent properties of surface soil have a significant influence on the evaluation of ground response. For low shear strain amplitude of about 10^{-6}, laboratory test results have often been compared with in situ soil data from geophysical explorations. However, because of sample disturbance and imperfect simulation of in situ stress conditions, it still seems unclear whether the laboratory data could duplicate in situ soil behavior up to relatively large strain levels prevailing during strong earthquakes.

In order to bypass the uncertainty in the laboratory, Miller et al (1975) developed an in situ impulse test for the measurement of shear modulus at varying strain levels within the strong motion region. 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 the crest and abutment records of strong motions. Since their results show somewhat different nature in comparison with the laboratory data, further research on actual dynamic properties of soil seems necessary for providing useful information.

The object of this research is to study the nonlinear properties of in situ soil and their relationship with experimentally determined values. In this paper, strain-dependent properties of surface soil during earthquakes are estimated by a rational procedure which only uses strong motion accelerograms obtained at the ground surface, and the results are compared with laboratory data. Finally, the relationships among nonlinear properties of soil, and stress and strain conditions developed in the soil are discussed.

ANALYTICAL PROCEDURE

Although the method conducted by Adbel-Ghaffar and Scott (1979) would be applicable to level ground, similar studies on level ground have not come to the authors' notice probably because of the unavailability of the strong motion accelerograms simultaneously obtained at the ground surface and at the bedrock. In this paper, therefore, the method for approximately predicting nonlinear properties of surface soil is developed from the strong motion accelerograms obtained only at the ground surface.

The method consists of spectrum and multi-reflection analyses in which the spectrum analysis could predict the nonlinear properties of soil varying with strain, and the reflection analysis offers the corresponding strain level induced in the soil. While similar studies for predicting shear strain in the soil from strong motion data assumed elastic properties (e.g. Sugimura, 1978), the shear strain is computed in this paper by approximately taking nonlinear soil properties into account on the basis of equivalent linear analysis. In order to analyze the soil properties, the following assumptions are introduced:

(1) The soil profile to be considered as an one-dimensional configuration is 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 the shear modulus, G, damping ratio, β, shear wave velocity, V_s, and mass density ρ.

(2) The earthquake ground surface motions are mainly due to the horizontal shear wave propagating from underlying bedrock, and the equivalent linear response analysis such as SHAKE (Schnabel et al, 1972) is applicable for analyzing the time histories of strong motion.

(3) Since it could be considered that the spectral shapes of the incident waves from bedrock to surface layer during an earthquake are relatively flat, the difference in the predominant period concerning ground surface motion could be

directly attributed to the nonlinear properties of the surface soil.

(4) The damping factor used in the calculation is defined in terms of the shear modulus ratio, G/G_o, by the following equation:

$$\beta = (h_{max} - h_o)\left(1 - \frac{G}{G_o}\right) + h_o \tag{1}$$

where h_{max} and h_o are constants and G_o is the shear modulus at a strain level of 10^{-6}.

Although some of the above assumptions cannot be verified or allowed in a strict sense, one could distinguish a general tendency concerning nonlinear properties of soil by using many records in the analysis. This is the reason that the source mechanism, propagation path, etc. which might affect the period are not discussed in the paper.

On the basis of the above assumptions, the first predominant period, T, of the spectrum analyzed on a strong motion record leads to the average shear wave velocity, V_s, of the surface soil:

$$V_{si} = \frac{4H}{T_i} \tag{2}$$

in which subscript i denotes the number of the record. Therefore the average shear modulus of the surface soil becomes

$$G_i = 16\rho\frac{H^2}{T_i^2} \tag{3}$$

Letting T_o be the predominant period at low strain level predicted from microtremors etc., Eq. (3) can be rewritten in the following form:

$$\frac{G_i}{G_o} = \left(\frac{T_o}{T_i}\right)^2 \tag{4}$$

Note that the shear modulus ratio is merely a function of the ratio between the predominant period at low strain and that prevailing during earthquakes.

Vertical propagation of shear waves through soil profile can be described by the wave equation:

$$\rho\frac{\partial^2 u}{\partial t^2} = G^*\frac{\partial^2 u}{\partial z^2} \tag{5}$$

in which G^* expresses the complex shear modulus defined by $G^* = G(1+2\beta i)$, t = time, u = displacement, and z = depth. Assuming that $\dot{f}$ and $\dot{g}$ are the particle velocities of the upward and downward shear waves at the top of each layer, respectively, Eq. (5) has a solution in terms of particle velocity, v, given by

$$v(t,z) = \frac{1}{V_i^*}\left\{\dot{f}\left(t + \frac{z}{V_i^*}\right) + \dot{g}\left(t - \frac{z}{V_i^*}\right)\right\} \tag{6}$$

in which V^* is complex shear wave velocity defined by $V^* = \sqrt{G^*/\rho}$.

Considering boundary conditions at the ground surface in which particle velocities of upward and downward waves can be identically equal to each other, the shear strain, γ, developed at any depth in the first layer at any time can readily be determined by

$$\gamma(t,z) = \frac{1}{2V_i^*}\left\{v_o\left(t + \frac{z}{V_i^*}\right) - v_o\left(t - \frac{z}{V_i^*}\right)\right\} \tag{7}$$

where v_o is the particle velocity at the ground surface which can easily be evaluated by integrating the strong motion records.

Because the method is applied either on the whole time histories of a record or on the partial time histories, it is assumed that the effective shear strain, γ_{eff}, corresponding to the shear modulus ratio defined by Eq. (4) could be appropriately represented by

$$\gamma_{eff} = \begin{cases} 0.65\gamma_{max} & \text{for whole record} \\ 0.85\gamma_{max} & \text{for partial record} \end{cases} \tag{8}$$

in which γ_{max} is the average of the maximum shear strains in the soil computed by Eq. (7).

Eqs. (4) and (7) enable one to predict nonlinear properties of soil in an approximate fashion. In the following analysis, h_{max} and h_o are assigned values of 0.25 and 0.01, respectively, although the values seem to have a minor effect on the results. Thus one could obtain strain-dependent properties of surface soil during earthquakes, by applying the method to a site where several earthquake records are available and where the soil profile is relatively simple. However, for obtaining meaningful results, it would be furthermore required that the impedance ratio between soil and bedrock, $(\rho V_s)_{soil}/(\rho V_s)_{rock}$, is less than about 0.3, because the strain induced in the lower layer under the conditions is so small that the nonlinear properties of the layer might have a negligible influence on the results.

NONLINEAR PROPERTIES AT HOSOSHIMA

The method is applied to Hososhima site which is located near a harbor in the eastern part of Kyushu in Japan. Since 1965, a strong motion accelerograph, SMAC-B2 Type, has been secured on the ground by the Port and Harbor Research Institute, the Ministry of Transport. Several strong motion accelerograms available in this study were recorded during the earthquakes whose characteristics are summarized in Table I. The stratigraphy of the site is well represented in Fig. 1 in which stiff soils consisting of recently deposited sand and diluvial clay, are stratified to a depth of about 50 m, and are underlain by Tertiary rock.

The empirical equation concerning shear wave velocity at low strain levels proposed by Ohta and Goto (1976) is given by

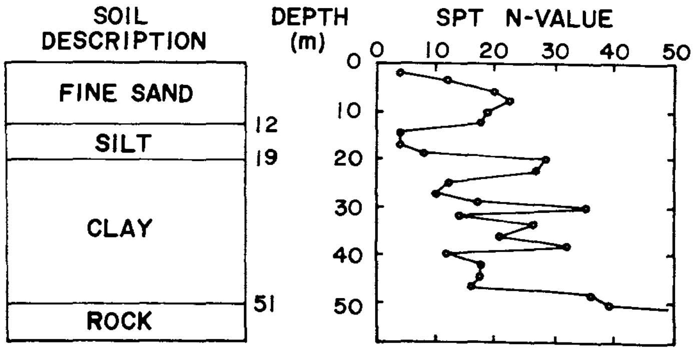

Fig. 1 Geological Conditions at Hososhima (after Tsuchida et al, 1967)

$$V_S = 69N^{0.17} D^{0.2} \begin{bmatrix} 1.0 \text{ alluvium} \\ 1.3 \text{ diluvium} \end{bmatrix} \begin{bmatrix} 1.0 & \text{clay} \\ 1.09 & \text{fine sand} \\ 1.07 & \text{medium sand} \\ 1.14 & \text{coarse sand} \\ 1.15 & \text{sandy gravel} \\ 1.45 & \text{gravel} \end{bmatrix} \tag{9}$$

in which N = SPT N-value and D = depth. Eq. (9) leads to the average shear wave velocity of about 260 m/s for the soil at a depth from 0 to 51 m. Considering that the predominant period of microtremors in the site is about 0.76 s and that the shear wave velocity for Tertiary rock is on the order of one thousand m/s, it seems reasonable to assume that the soil to the depth of 51 m and Tertiary rock can be classified into surface layer and bedrock, respectively, for analytical purposes.

Fig. 2 shows the acceleration time histories of E-W component during the 4/01, 1968 earthquake which have a peak acceleration of 242 cm/s^2. The predominant period in the record is as much as 50 percent greater than the natural period of the microtremors, suggesting that the behavior at a small vibration level would not provide enough information to evaluate the soil behavior during strong earthquakes.

Typical velocity response spectra for the whole time histories of a record that are closely related to the Fourier acceleration spectra are shown in Fig. 3. The velocity responce spectra were computed by simultaneously applying two orthogonal hirozontal records of an earthquake to single-degree-of-freedom systems (Kobayashi and Nagahashi, 1977). Note that the predominant period generally increases as the peak acceleration increases, whereas the shape of the spectra is almost similar. This trend could have an indication of strain-dependent properties of surface soil in connection with Eq. (4).

The reduction in shear modulus with an increase in shear strain at the site is computed by the method for N-S and E-W components, respectively, and the results are summarized in Fig. 4. Although the values predicted from earthquake records show a considerable variation, the general trend in which the shear modulus ratio decreases with increasing shear strain can be apparent. For comparison purposes, Fig. 4 also shows the laboratory data by Iwasaki et al (1979) for clay conducted under the confining stresses associated with the site. It can be seen in the figure that the analytical results are reasonably consistent with the laboratory test data.

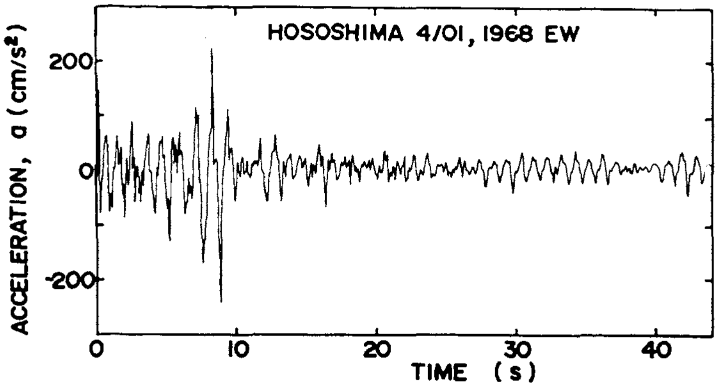

Fig. 2 Acceleration Time Histories during The 4/01, 1968 Earthquake

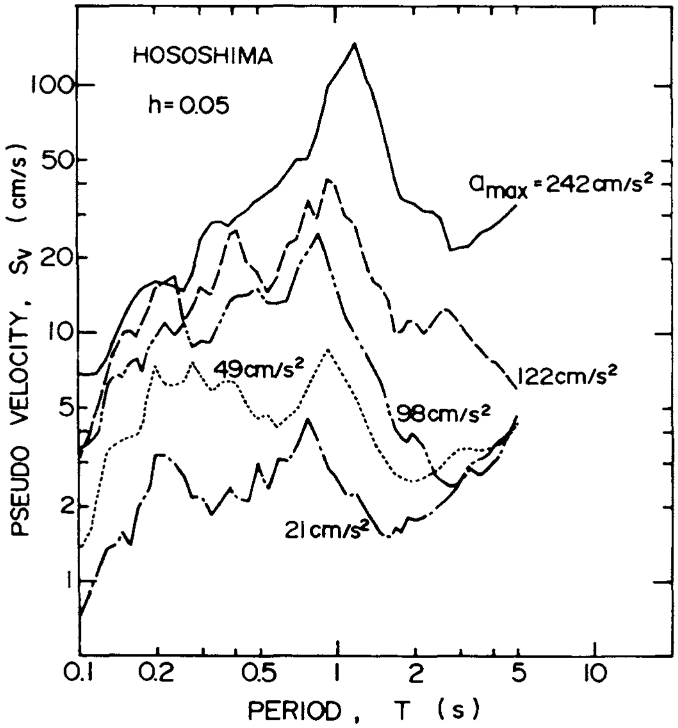

Fig. 3 Velocity Response Spectra

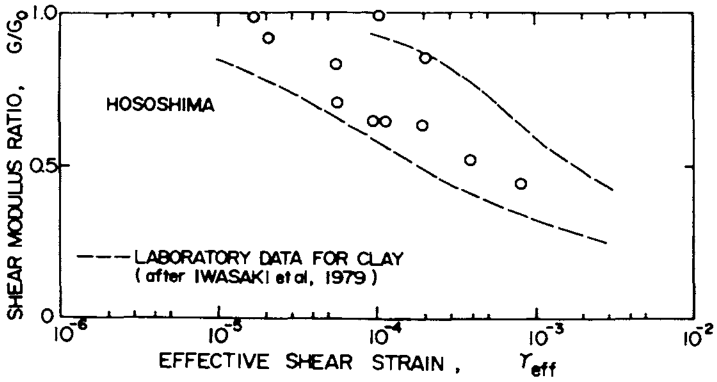

Fig. 4 Relationship between G/Go and γeff for Whole Records at Hososhima Site

Table I Strong Motion Records Used

Date	α_{max} (cm/s^2) NS	α_{max} (cm/s^2) EW	Date	α_{max} (cm/s^2) NS	α_{max} (cm/s^2) EW
HOSOSHIMA			HIROO		
4/01, 1968	182	242	10/26, 1965	137	135
8/06, 1968	45	39	9/19, 1967	97	64
4/21, 1969	63	98	5/16, 1968	299	308
7/26, 1970A	88	122	9/21, 1968	163	138
7/26, 1970B	49	49	10/08, 1968	140	185
6/22, 1972	21	20	1/21, 1970	605	547
KUSHIRO J.M.A.			KUSHIRO HARBOR		
11/15, 1961	110	111	10/26, 1965	73	58
2/21, 1962	113	170	5/16, 1968	39	47
4/23, 1962	513	255	8/07, 1968	40	72
7/18, 1962	87	83	8/12, 1969	40	37
6/23, 1964	85	109	1/21, 1970	38	30
10/26, 1965	272	118	5/11, 1972	94	66
11/04, 1967	285	357	6/17, 1973	166	120

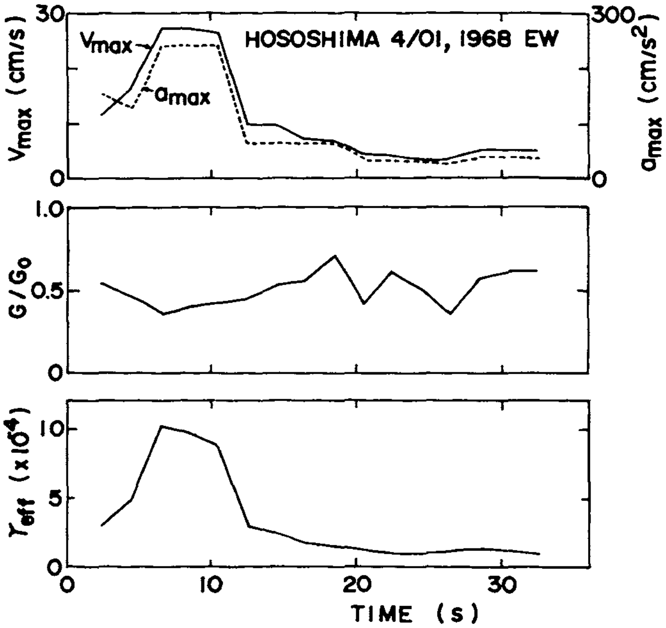

Fig. 5 Time Histories of G/G_0, Particle Verocity, Acceleration and Shear Strain

In order to study the relationship between shear modulus and shear strain during an earthquake, running Fourier spectrum analysis having a window time of 5 s and a step time of 2 s is conducted, and the effective shear strain is computed for the corresponding time histories of the record. Typical time histories of velocity, acceleration, shear modulus, and shear strain are presented in Fig. 5 for the first 30 s of the record shown in Fig. 2. Although the amplitude of acceleration after about 15 s is small, the value of G/G_0 sometimes does become below 0.5 presumably because of the presence of surface waves. It could be noted, however, that the reduction of shear modulus depends primarily on the shear strain amplitude.

For examining the nonlinear properties of soil in further detail, the relationships between shear modulus ratio and shear strain until about 15 s after an arrival of first shear wave are plotted in Figs. 6 and 7 for some earthquakes, because the record of this duration seems to consist mainly of shear waves. The number indicated in the figure is the starting time from which the nonlinear properties of soil are computed for a period of 5 s. Also shown in the figure are laboratory test results for clay. The computed results show a little scatter especially at small strain levels. Nevertheless, it is noteworthy that the nonlinear characteristics estimated from strong motion accelerograms are in quite good agreement with the laboratory test data over the strain range from 10^{-5} to 10^{-3}.

While it has been pointed out that laboratory and in situ shear moduli may differ significantly (Yoshimi et al, 1977), the accordance between the analytical results and laboratory data reported here indicates that carefully conducted laboratory studies appear to simulate the field behavior, as far as the G/G_0 versus γ relationship is concerned. It can be noted that the results on whole time histories in Fig. 4 are compatible with the results on partial time histories in Figs. 6 and 7, therefore the analysis will be conducted on whole time histories hereafter.

SHEAR MODULUS DURING EARTHQUAKES

The method is also applied to the other three sites. The characteristics of the sites and earthquakes used in the analysis are summarized in Tables I and II. The computed results are shown in Fig. 8 along with laboratory test results. As may be expected, all the data analyzed fall within the range of laboratory data

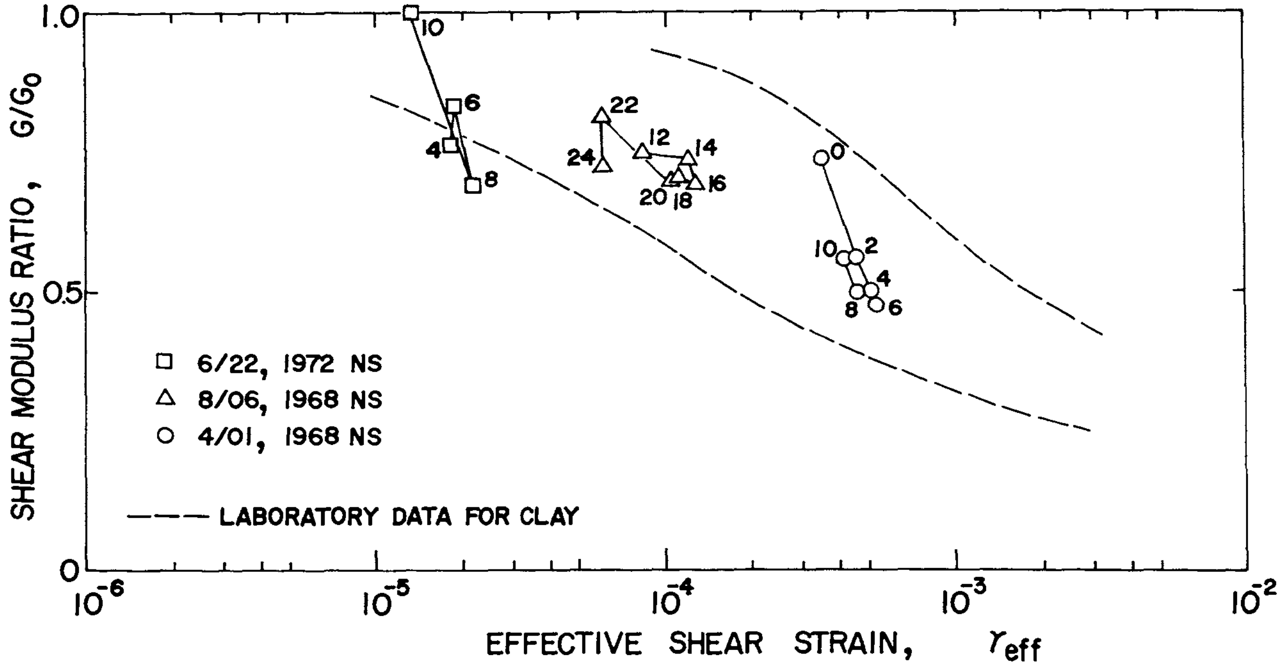

Fig. 6 Relationship between G/G_0 and γ_{eff} for Partial Records at Hososhima Site

and exhibit material degradation characteristics of in situ soil with shear strain.

Figs. 9 and 10 show the relationships between G/G_o, and peak ground acceleration, α_{max}, and peak ground particle velocity, v_{max}, respectively. Since there is a large amount of scatter in Fig.9, the relationship concerning acceleration for each site is barely defined by a curve as shown in the figure. On the other hand, the dashed line in Fig. 10 shows a fairly well-defined trend in which G/G_o generally decreases with increasing particle velocity, irrespective of site geological conditions. Thus, the

Table II Characteristics of the Sites

Site	Depth (m)	To (s)	ρ (t/m^3)	V_{so} (m/s)	Soil
HOSOSHIMA	51	0.76	1.80	268	sand-clay
HIROO	6	0.17	1.80	141	sand
KUSHIRO J.M.A.	14	0.26	1.75	215	silt-sand
KUSHIRO HARBOR	52	0.94	1.90	221	sand

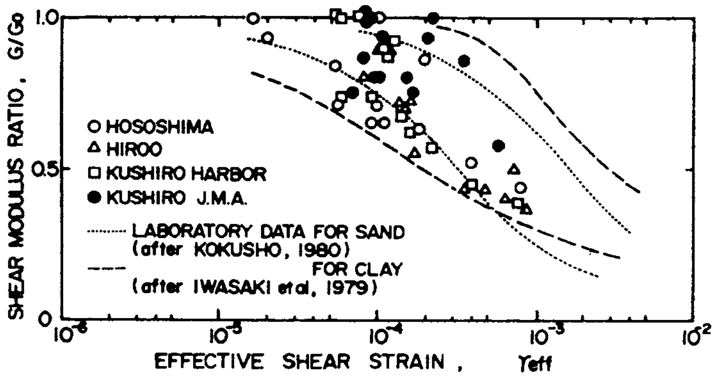

Fig. 8 Relationship between G/G_o and γ_{eff}

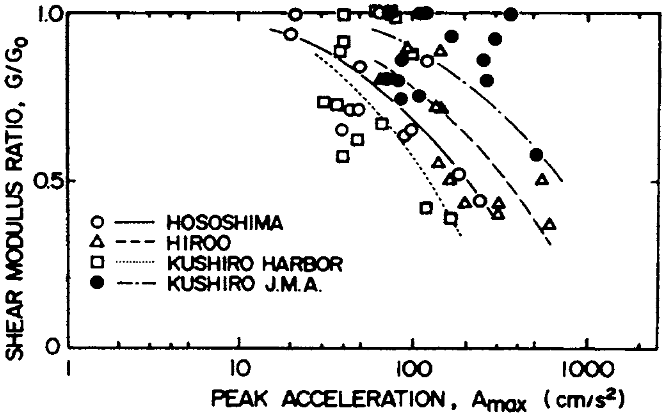

Fig. 9 Relationship between Shear Modulus Ratio and Peak Ground Acceleration

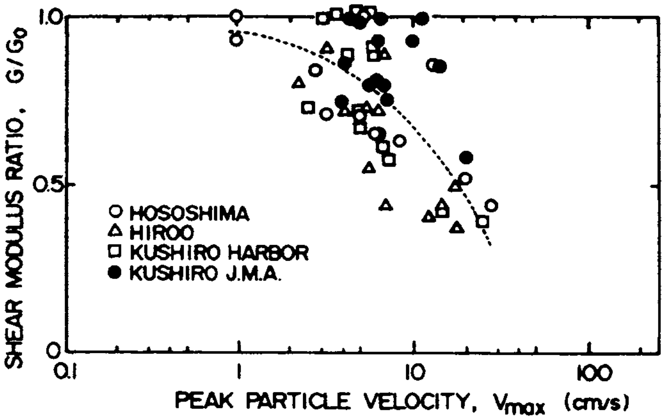

Fig. 10 Relationship between Shear Modulus Ratio and Peak Ground Particle Velocity

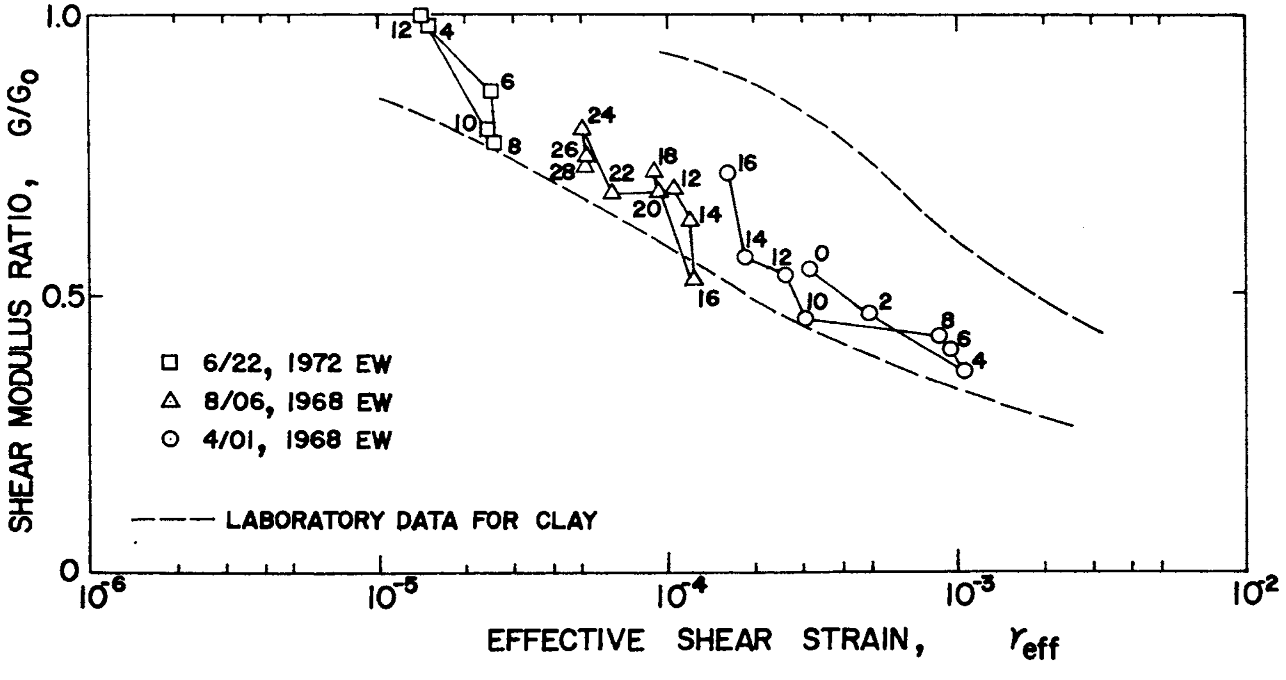

Fig. 7 Relationship between G/G_o and γ_{eff} for Partial Records at Hososhima Site

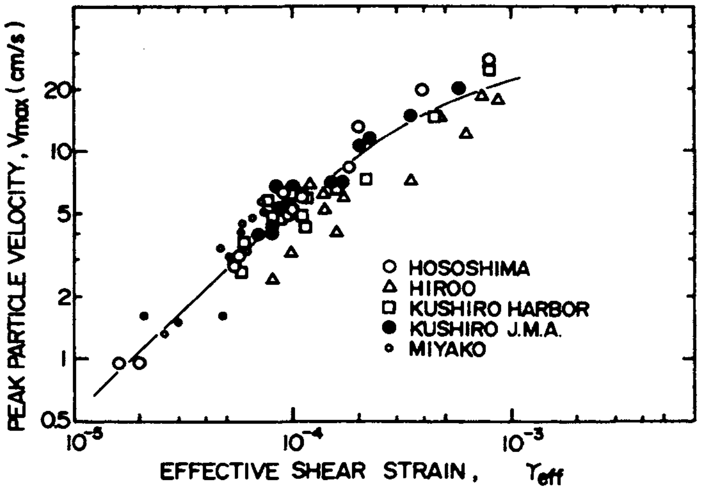

Fig. 11 Relationship between γ_{eff} and v_{max}

nonlinearity of the surface soil would rather be better correlated with peak velocity at the ground surface than with peak acceleration, within the data used. It is interesting to note that the reduction in shear modulus is particularly sensitive to the change in velocity above 5 cm/s.

Fig. 11 shows the relationship between shear strain amplitude and peak particle velocity. Large symbols are the data used in this study and the small symbols are extracted from the first author's personal file. It is clearly observed that the data lie within a narrow band regardless of the site conditions.

It can be noted that the curve in the log-log paper is inclined at a slope of 1 to 1 within a strain range below 10^{-4}, indicating that v_{max} is directly proportional to shear strain, i.e., the elastic properties are maintained in this strain level. On the contrary, above 10^{-4} strain level, the relationship is no longer linear and the inclination gradually decreases with an amplitude of shear strain, probably because of the significant material degradation of surface soil.

The analysis described herein can unfortunately provide no information concerning in situ damping factors during earthquakes. More data on the damping characteristics therefore are needed, because the ground response to earthquakes is greatly affected by them as well as by shear moduli.

CONCLUSIONS

On the basis of the analytical studies for approximately estimating strain-dependent shear modulus of surface soil from strong motion accelerograms obtained at the ground surface, the following conclusions may be made:

(1) The fact that the first predominant period of surface soil increases with an increase in acceleration offers an indication of nonlinear properties of surface soil.

(2) Time histories of shear modulus and shear strain could be obtained during an earthquake, which indicate the significant degradation of shear modulus with shear strain.

(3) The strain dependent shear modulus evaluated from earthquake ground motions are in good agreement with the previous laboratory test results in a strain range from 10^{-5} to 10^{-3}.

(4) The shear modulus ratio is better correlated with peak particle velocity at the ground surface than with peak acceleration irrespective of the site geological conditions.

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