VIBRATION CHARACTERISTICS OF DYNAMIC MODELS OF SOIL AND THEIR APPLICABILITY TO THE FIELD

T. Tazoh (1)
S. Nakahi (1)
K. Shimizu (1)
H. Yokota (1)
Presenting Author: K. Shimizu

SUMMARY

Studies are made to examine (1) dynamic characteristics under the steady-state loading, and (2) applicability to randam waves with regard to modifications of the Ramberg-Osgood and Hardin-Drnevich models which are used to express the hysteretic stress-strain relations of soil. It is found from the result that in connection with (1) there is a trend for response to be suppressed markedly with the modified Hardin-Drnevich model. Concerning (2), it is found that the modified Ramberg-Osgood model is effective in the nonlinear dynamic analysis if the model is used according with the procedure indicated in the present paper. In addition, based on comparisons with observed records, it is found that linear analysis is inadequare when the maximum strain level of soil is of the order of 10^{-3}, and it is necessary to consider nonlinearity.

INTRODUCTION

The Ramberg-Osgood and Hardin-Drnevich models are representative of dynamic models showing the hysteretic stress-strain relations of soil.

The Ramberg-Osgood model had been proposed originally to analyse nonlinear behaviors of metal materials and is not in the effective functional expression for soil problems. The Hardin-Drnevich model is introduced for soil based on the hyperbolic-type stress-strain relationship proposed by R.L.Kondner. However, in this model the area surrounded by the hysteresis curve, i.e., the energy dissipated per cycle of vibration is only represented. Thus, a distinct expression concerning the hysteresis curve is not given. Then, modifications have been devised for both models (Ref. 1,2), and they are used to analyse the nonlinear earthquake response by the step-by-step integration scheme.

The paper presents the research results on

(1) dynamic characteristics of soil under the steady-state loading
(2) nonlinear earthquake response analysis of soil based on observed records

in order to investigate what kinds of characteristics these modified models possess under the steady-state loading and what degrees they would be applicable to the actual field.

DYNAMIC CHARACTERISTICS OF SOIL UNDER STEADY-STATE LOADING

Resonance Curve and Phase Curve

The formulation for the steady-state response characteristics of each model was made by the slowly varying parameters method. When the slowly

(1) Shimizu Construction Co., Ltd., Tokyo, Japan

varying parameters method is employed, the resonance and phase curves of a nonlinear system with one degree of freedom are given by the following equations assuming strain γ as $\gamma = \gamma a(t)\sin(pot + \psi(t)) \equiv \gamma a(t)\sin\theta(t)$ for external force (applied load) P sin pot (Fig. 1).

Resonance curve: $C^2(\gamma a) + \{S(\gamma a) - \gamma a Po^2\}^2 = Q^2$ .... (1)

Phase curve: $\tan\psi = -C(\gamma a)/\{S(\gamma a) - \gamma a Po^2\}$

where,

$$C(\gamma a) = \frac{1}{\pi}\int_0^{2\pi} R(\gamma a \sin\theta)\cos\theta d\theta$$

$$S(\gamma a) = \frac{1}{\pi}\int_0^{2\pi} R(\gamma a \sin\theta)\sin\theta d\theta \quad \text{.............. (2)}$$

$Q = P/m\ell$ and $R(\gamma)$ express the hysteresis curves of dynamic model of soil.

Modified Ramberg-Osgood Model (Modified R-O Model)

The skeleton curve and the hysteresis curve of the modified R-O model proposed by F.Tatsuoka et al. are given by the following equations:

Skeleton curve: $\gamma = \frac{\tau}{G_o}(1 + \alpha|\tau|^\beta)$

Hysteresis curve: $\frac{\gamma \pm \gamma a}{2} = \frac{\tau \pm \tau a}{2G_o}(1 + \alpha|\frac{\tau \pm \tau a}{2}|^\beta)$ .... (3)

where, $\beta = \frac{2\pi h_{max}}{2-\pi h_{max}}$, $\alpha = (\frac{2}{G_o\gamma r})^\beta$, τ and γ are stress and strain, G_o is an initial shear modulus, γr is reference strain, and h_{max} is a damping coefficient when γ is infinitely large.

With $\xi = \gamma/\gamma r$ and $\xi_a = \gamma a/\gamma r$, Eq. 2 shown in the form of $C(\xi a)$ and $S(\xi a)$ will be

$$C(\xi a) = \frac{1}{2} h_{max} (\frac{2\tau a}{G_o\gamma r})^{\beta+2}/\xi a$$

$$S(\xi a) = \frac{2}{\pi\xi_a}\int_{-\xi a}^{\xi a} \frac{\tau}{G_o\gamma r} g(\xi) d\xi \quad \text{.............. (4)}$$

where, $g(\xi) = \xi/\sqrt{\xi a^2 - \xi^2}$. The resonance curve and phase curve of this model will be shown in Fig. 2.

Modified Hardin-Drnevich Model (Modified H-D Model)

The skeleton curve and the hysteresis curve, determined by Masing's law, of the modified H-D model are given by the following equations:

Skeleton curve: $\tau = \frac{Go\gamma}{1 + |\gamma/\gamma r|}$

Hysteresis curve: $\frac{\tau \pm \tau a}{2} = \frac{Go(\gamma \pm \gamma a)/2}{1 + |(\gamma \pm \gamma a)/2\gamma r|}$ .... (5)

The $C(\xi a)$ and $S(\xi a)$ are expressed in the following equations:

$$C(\xi a) = \frac{4}{\pi}\xi a\{2/\xi a - 1/(1 + \xi a) - 2/\xi a^2 \cdot \log(1 + \xi a)\}$$

$$S(\xi a) = 8/\xi a\{(1 + \xi a/2)/\sqrt{1 + \xi a} - 1\} \quad \text{.............. (6)}$$

and the resonance curve and the phase curve will be shown in Fig. 3.

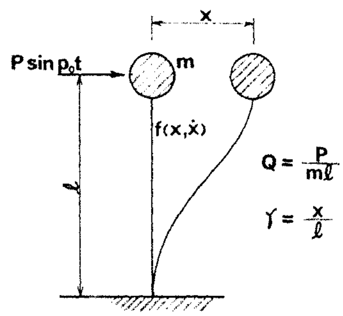


Fig.1 Nonlinear Model of One DOF System

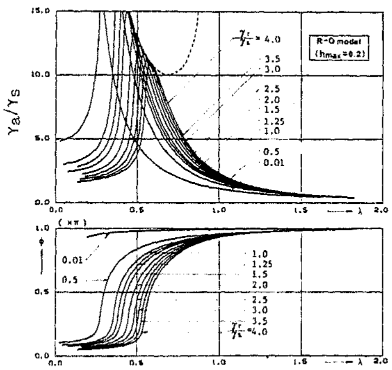


Fig.2 Resonance Curves and Phase Angle Curves (Modified R-O Model, hmax=0.2)

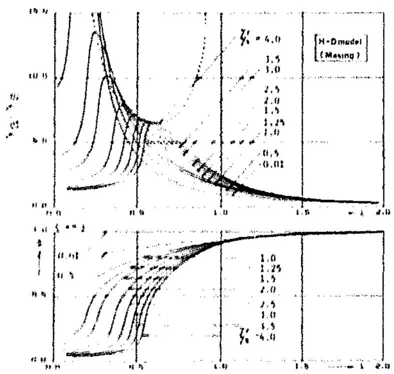


Fig.3 Resonance Curves and Phase Angle Curves (Modified H-D Model, Masing type)

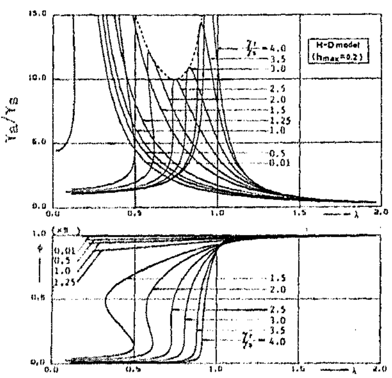


Fig.4 Resonance Curves and Phase Angle Curves (H-D Model, hmax=0.2)

Hardin-Drnevich Model (H-D Model) (Ref. 3)

The steady-state response characteristics of the H-D model are also examined in order to compare with those of the modified models. The skeleton curve of the H-D model is given by a following equation:

$$\tau = \frac{G_o \gamma}{1 + |\gamma/\gamma r|} \qquad \ldots\ldots\ldots\ldots\ldots\ldots \quad (7)$$

And the energy dissipated per cycle of vibration $\Delta W(\gamma a)$ is prescribed by the equation below.

$$\Delta W(\gamma a) = 2\pi h_{max} G^2 \gamma a^2 (1/G - 1/G_o) \qquad \ldots\ldots\ldots\ldots\ldots\ldots \quad (8)$$

where, $G = \tau a/\gamma a$.

Incidentally, the relationships for the resonance and phase curves shown in Eq. (1) can be similarly deduced by Fourier's expansion with $R(\gamma)$ as expansion order $n = 1$. This has an extremely significance in considering the behavior of the H-D model which does not provide a distinct expression to the hysteresis curve under the steady-state forced vibration. When the hysteresis curve $R(\gamma)$ is expressed by a skeleton curve $\tau s(\gamma)$ and a damping curve $\tau_d(\gamma)$ as,

$$R(\gamma) = \tau s(\gamma) \pm \tau d(\gamma), \; d\gamma/dt \gtrless 0 \qquad \ldots\ldots\ldots\ldots (9)$$

the sine term subjected to Fourier's expansion will correspond to the skeleton curve and cosine term to the damping curve. Accordingly Eq. (2) can be written as

$$C(\gamma a) = \frac{1}{\pi\gamma a}\oint \tau d(\gamma)d\gamma = \Delta W(\gamma a)/(\pi\gamma a)$$
$$S(\gamma a) = \frac{1}{\pi}\int_0^{2\pi} \tau s(\gamma a \sin\theta)\sin\theta d\theta \qquad \ldots\ldots\ldots\ldots (10)$$

As expressed before in the form normalized by γ_r, $C(\xi a)$ and $S(\xi a)$ will be expressed as follows:

$$C(\xi a) = 2h_{max}\xi a^2/(1+\xi a)^2$$
$$S(\xi a) = 4(\xi a - \pi/2 + I)/(\pi\xi a) \qquad \ldots\ldots\ldots\ldots (11)$$

where,

$$I = 2\{\tan^{-1}\sqrt{(1+\xi a)/(1-\xi a)} - \tan^{-1}(\xi a/\sqrt{1-\xi a^2})\}/\sqrt{1-\xi a^2}, \; 1>\xi a^2$$
$$I = \ln\{(1+\xi a+\sqrt{\xi a^2-1})/(1+\xi a-\sqrt{\xi a^2-1})\}/\sqrt{\xi a^2-1}, \; 1<\xi a^2 \quad \ldots(12)$$
$$I = 1, \; 1=\xi a^2$$

When the resonance and phase curves are plotted using Eq. (1), the results will be shown in Fig. 4.

Comparisons of Each Model Steady-State Response Characteristics

The resonance curves in Fig. 2 through Fig. 4 are shown with $\gamma r/\gamma s$ as a parameter. In this figure, frequency ratio $\lambda = Po/\omega n$ (ωn being the natural circular frequency of the system determined by Go) is taken on the abscissae, and dynamic maximum strain γa against static maximum strain γs, i.e., $\gamma a/\gamma s$, is taken on the ordinates.

In the figures on resonance curves, it may be seen that the peak values and shapes of resonance curves of each model vary with the value of the parameter $\gamma r/\gamma s$, and it can be understood that there is a minimum value of $\gamma a/\gamma s$ for the state of resonance below which the value does not exist. Further, from the figures on phase curves, it may be seen that the peak of the resonance curve is given where the phase angle is $\pi/2$.

The disparities in the vibration characteristics of dynamic models of soil appear prominently in the resonance curves. On comparison of the modified H-D and H-D models, a considerable difference exists between the two, i.e., the amplitude ratio of modified H-D model is extremely suppressed compared with that of the H-D model. This is probably due to the fact that the modified H-D model for which the hysteresis curve is determined applying Masing's law always takes $h_{max} = 2/\pi$, therefore the damping force acts substantially.

On comparison of the modified R-O model and H-D model in the same value of h_{max}, a large difference exists in the large values of resonance frequencies. And the shapes of resonance curves for modified R-O model is in good agreement with that for modified H-D model. However, it is thought that the peculiarity of the modified H-D model wherein the value of h_{max} always takes a constant $2/\pi$ will prove to be a great problem for practical purposes.

be defined properly as the damping constant when γ is infinitely large. But if the value of h_{max} were fixed in this manner on the modified R-O model, there will be a considerable deviation in part (for example, as shown in Fig. 6(a)) between the theoretically defined $G/G_o \sim \gamma$ and heq $\sim \gamma$ curves and the experimental curve of soil (the proposed curve of Ref. 5 in this case).

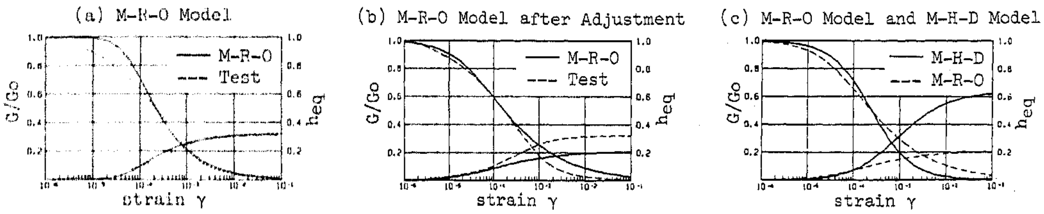


Fig. 6 $G/G_o \sim \gamma$ Relation and $h_{eq} \sim \gamma$ Relation

Incidentally, the influence of this deviation on the response result is great, therefore it is important to reduce such deviations for the accuracy of analysis. Looking at the theoretical equations of the $G/G_o \sim \gamma$ and $h_{eq} \sim \gamma$ curves of the modified R-O model, these can be written as follows with h_{max} as the parameter.

$$\frac{G}{G_o} = \frac{1}{1 + (2\frac{\gamma}{\gamma r}\frac{G}{G_o})^{\beta}} \qquad \qquad \cdots\cdots\cdots\cdots \quad (13)$$

$$h_{eq} = h_{max}\ (1 - \frac{G}{G_o})$$

where $\beta = \frac{2\pi h_{max}}{2-\pi h_{max}}$. In Fig. 7 values of the above equation are plotted with a parameter h_{max}.

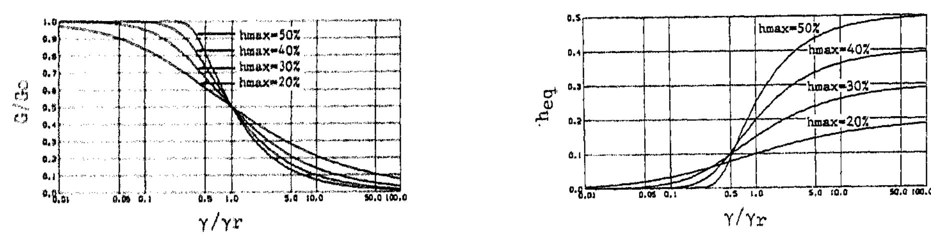


Fig. 7 $G/G_o \sim \gamma/\gamma r$ Relation and $h_{eq} \sim \gamma/\gamma r$ Relation

From this figure, the $G/G_o \sim \gamma$ curve can be varied depending on the value of h_{max}. By manipulating the value of h_{max}, the $G/G_o \sim \gamma$ curve of the modified R-O model and the experimental curve of soil can be approximated within the strain levels produced at the each layer of soil.

The constants h_{max} of the modified R-O model were all determined by this procedure. Figure 6(b) shows an example of approximation of the experimental curve under strain level of 10^{-4} in Fig. 6(a).

Analysis Results and Considerations

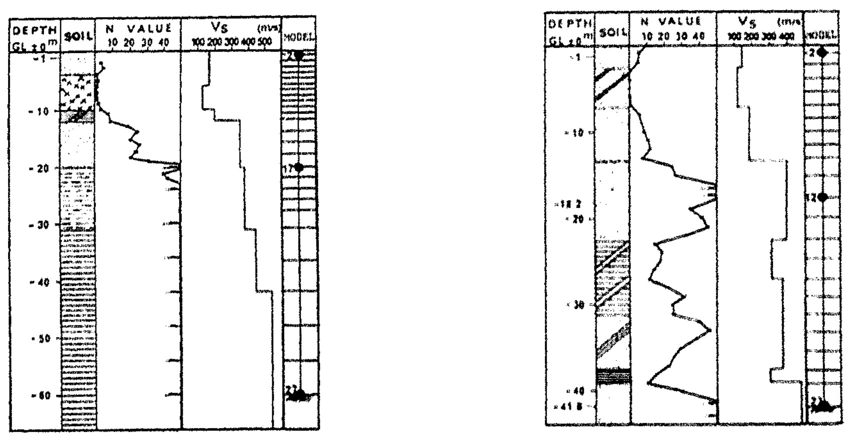
To compare results obtained by different methods, earthquake response analyses by a linear model were also performed. Linear analyses were made by

NONLINEAR EARTHQUAKE RESPONSE ANALYSES
OF SOIL BASED ON OBSERVED RECORDS

In this chapter, earthquake records observed at two different soft soil deposits are used to perform nonlinear earthquake response analyses (Ref. 4), and a study is made to examine the applicability of the dynamic model of soil to the actual field based on comparisons between analytical results and observed records.

Soil Condition and Accelerometer Locations

The soil profiles and the locations where accelerometers were buried are shown in Fig. 5. The sites of earthquake observations were Shibaura, Minato-ku, Tokyo, and Sodegaura, Kimitsu-gun, Chiba-ken. The accelerometers are buried at depths of G.L. -1 m, G.L. -20 m, and G.L. -60 m at Shibaura, and G.L. -1 m, G.L. -18 m, and G.L. -42 m at Sodegaura. The earthquake records used for analyses were observed for the Chiba-ken Chubu Earthquake (M = 6.1, D = 80 km) of September 25, 1980.



(at Shibaura) (at Sodegaura)

Fig. 5 Soil Profiles and Analysis Models

Analytical Models and Soil Properties

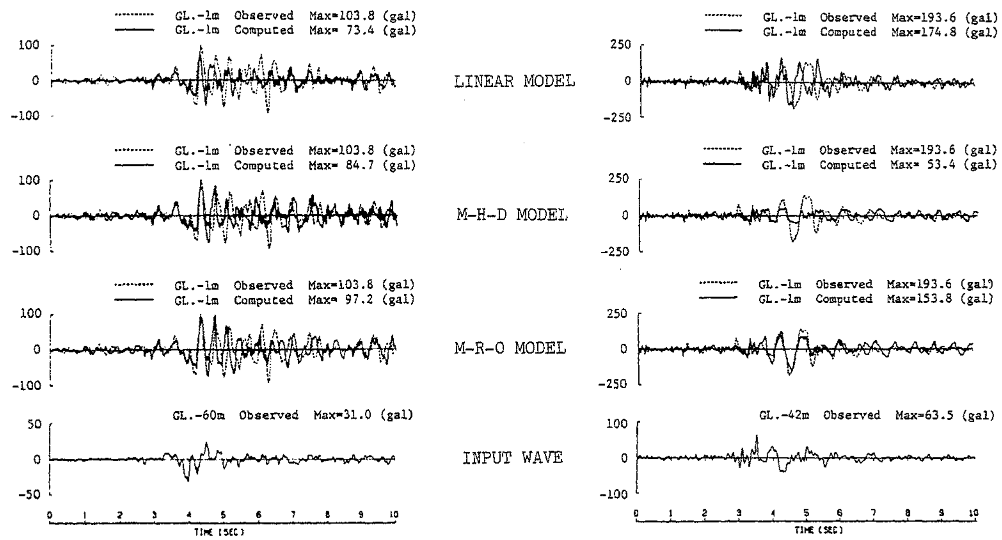
The analysis models are shear-type lumped-mass systems, with 26 mass points for Shibaura soil and 22 for Sodegaura soil. The models of the two soils are shown in Fig. 5.

For each of the soils, the initial shear modulus G_o was obtained from $G_o = \rho Vs^2$. With regard to reference strain γr, since dynamic tests had not been performed on both Shibaura and Sodegaura soils, strains corresponding with $G/G_o = 0.5$ were taken based on the $G/G_o \sim \gamma$ curve proposed by the Ministry of Construction Public Works Research Institute (Ref. 5).

Damping Constant h_{max} of Modified Ramberg-Osgood Model

The constants of the modified H-D model are G_o and γr. On the other hand, those of the modified R-O model are G_o, γr and h_{max}. The value of h_{max} would the mode synthesis method. The damping constants (Ref. 6) used are as follows: $h_1 = 0.084$, $h_2 = 0.020$, $h_3 = 0.030$, $h_4 - h_{25} = 0.018$ for Shibaura soil and $h_1 = 0.106$, $h_2 = 0.053$, $h_3 = 0.020$, $h_4 = 0.007$, and $h_5 - h_{22} = 0.005$ for Sodegaura soil.

In Figure 8, the results obtained by these analyses are compared with observed records. In all cases the dashed lines are observed waves and the solid lines calculated waves. What should be noted with respect to the results are the response characteristics for both sites around peak acceleration from during 3 sec to 6 sec.

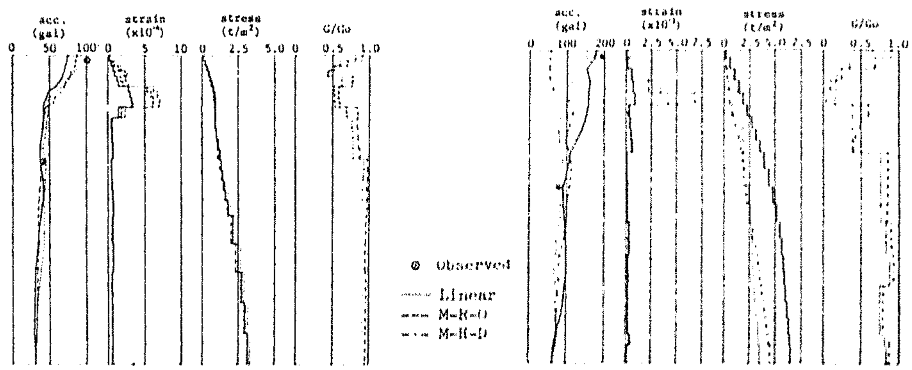


(at Shibaura) Fig. 8 Observed and Computed Waves (at Sodegaura)

Prominent disparities are not recognized among differences in dynamic models of soils including the results of linear analyses, from the analytical results of Shibaura site. In analysis of Sodegaura site, there exist significant differences among results of those models. In linear analyses considerable phase lags are produced between observed and calculated waves around peak accelerations.

In nonlinear analyses, the phases of calculated waves obtained by R-O model and H-D model are in good agreement with that of the observed waves. However, the amplitude of the calculated waves for the modified H-D model is greatly suppressed around the peak acceleration. As described in the previous chaper, this is caused by the uniqueness of the modified H-D model, i.e., as shown in Fig. 6(c), this is due to the fact that this model gives excessive damping in the range of large strain. On the other hand, the calculated wave obtained by the modified R-O model for which the value of hmax was determined by the method in this paper, agree quite well with the observed wave.

It is found from the distribution diagram shown in Fig. 9 that nonlinear analysis is not significant in the order of 10^{-4} for maximum shearing strain (from the distribution diagram for Shibaura site). When maximum strain is of the order of 10^{-3} (from the distribution diagram for Sodegaura site), a linear model is inadequate, therefore the modified R-O model should be applied to simulate the observed waves.



(at Shibaura) Fig. 9 Maximum Response Distribution (at Sodegaura)

CONCLUSIONS

Studies are made to examine (1) dynamic characteristics under the steady-state loading, and (2) applicability to randam waves with regard to modifications of the Ramberg-Osgood and Hardin-Drnevich models. Consequently, the next results are obtained.

(1) The steady-state response characteristics of the modified R-O model and the modified H-D model including the H-D model are clarified.

(2) It is found from the comparisons between analytical results and observed records that the modified R-O model should be applied to simulate the observed waves over strain level of 10^{-3}.

ACKNOWLEDGEMENTS

The earthquake observation records of Sodegaura soil used in this paper were obtained at the Sodegaura Plant of Tokyo Gas Co., Ltd. The authors extend their sincere gratitude to the persons concerned of Tokyo Gas Co.,Ltd. for making possible utilization of these records.

REFERENCES

(1) Tatsuoka, F., and Fukushima, S., "Stress-Strain Relation of Sand for Irregular Cyclic Excitation (I), (II)," Report of the Institute of Industrial Science, University of Tokyo, Vol. 30, Nos. 9, 10, 1978.

(2) Kokusho, T., and Sakurai, A., "On the Modified Hardin-Drnevich Model," Preprint of the 33rd Annual Meeting, JSCE, 1978.

(3) Ohira, A., Tazoh, T., Nakahi, S., and Toki, A., "Steady-state Response Characteristics of Hardin-Drnevich Model," Proceedings of the 16th JSSMFE, 1981.

(4) Tazoh, T., Yokota, H., Toki, A., Shimizu, K., and Shimada, M., "Several Considerations Concerning the Results of Nonlinear Earthquake Response Analysis of Soil Based on Observed Records," Proceedings of the 17th JSSMFE, 1982.

(5) Iwasaki, T., Tatsuoka, F. and Takagi, Y., "Shear Moduli of Sands under Cyclic Torsional Shear Loading," Soils and Foundations, Vol. 18, No.1, 1978.

(6) Yokota, H., Watanabe, H., Shioya, K., and Ishii, K., "Underground Earthquake Observations at Soft Ground in Tokyo and Environs," Reports of the Research Laboratory of Shimizu Construction Co., Ltd., No.30, 1979.