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# APPLICATION RULE OF ONE-DIMENSIONAL FREQUENCY-DOMAIN WAVE PROPAGATION ANALYSIS

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## ABSTRACT

The authors examined the reliability of the linear and non-linear one-dimensional wave propagation analysis by frequency-domain approach through simulation study using recorded motions obtained at two vertical arrays and the geotechnical data obtained in-situ. It was found that the method is sufficiently reliable in the present form in which frequency-independent damping and the reference strain level by factor of 0.65 to the maximum strain are assumed, if the analysis were supported by a carefully determined velocity profile of the site and strain-dependency of soil layers. Following what have been obtained through the above study, the authors proposed a practical rule to be followed in application of the method, in order to keep the results reliable.

## 1 INTRODUCTION

The linear and non-linear one-dimensional wave propagation analysis by frequency-domain approach such as that followed by computer code SHAKE has been practically very popular, whereas there have been some arguments whether the damping is really frequency-independent or the fraction of 0.65 to the maximum strain is adequate to modulate working shear modulus.

Nozawa[1988] in his validation study of the analysis method has concluded that in order to well reproduce the ground surface motions using the underground motions both obtained at the vertical array of Shin-Fuji substation in the 1983 East Yamanashi-ken earthquake, the coefficient multiplied to the maximum strain for determining the working strain-dependent soil moduli and damping should be modulated from the standard value of 0.65 to 0.3 and also it was necessary to introduce the damping factor inversely proportional to frequency for compensating excessive attenuation nature of high frequency components in the analysis.

Using the computer code like the SHAKE, we have been widely defining the control motions in the dynamic analysis models of not a few critical structures such as nuclear facilities and lifeline structures. And, in most cases of past simulation experience using the recorded motions and geotechnical data then available, we have not found the necessity to modify the coefficient to such level as 0.3, even though Ohsaki[1982] suggested the value could be 0.45 to the maximum strain while the value ranging from 0.55 to 0.65 was recommended by Schnabel et al[1972].

It is not our main goal of this study to prove the adequacy of the coefficient of 0.65; however, since the arbitrary choice of the coefficient to the maximum strain to determine the reference strain to modulate strain-dependent soil properties and the said high frequency attenuation characteristics in frequency domain method may be still the unresolved problems which can seriously affect on the results of dynamic analyses of non-linear soil behavior, author's group has examined the validity of the method through simulation analyses of the recorded motions at the vertical array installed at a soil site of Goi Thermal Power Plant in Chiba, Japan, from the stand point of practicing engineers frequently using the analysis method as the fundamental tool for various dynamic analyses. Following the results obtained through the above validation study, Katayama et al [1992] has pointed out that the method is reliable and very useful if it were used based upon realistic velocity profile and sufficiently reliable strain-dependent soil properties of the subsurface layers and it was also proposed to include additionally a few percent of initial damping in the non-linear soil response analysis which provides some unknown damping effect necessary for explaining the linear soil response recorded at the vertical array. In this paper, the authors analyze a new set of recorded ground motions obtained by seismometers installed in multi-depths at another vertical array and confirm the necessity to introduce the initial damping value into the analysis and finally try to propose a practical rule to be followed in application of the analysis method based upon what have been obtained through this and the previous study.

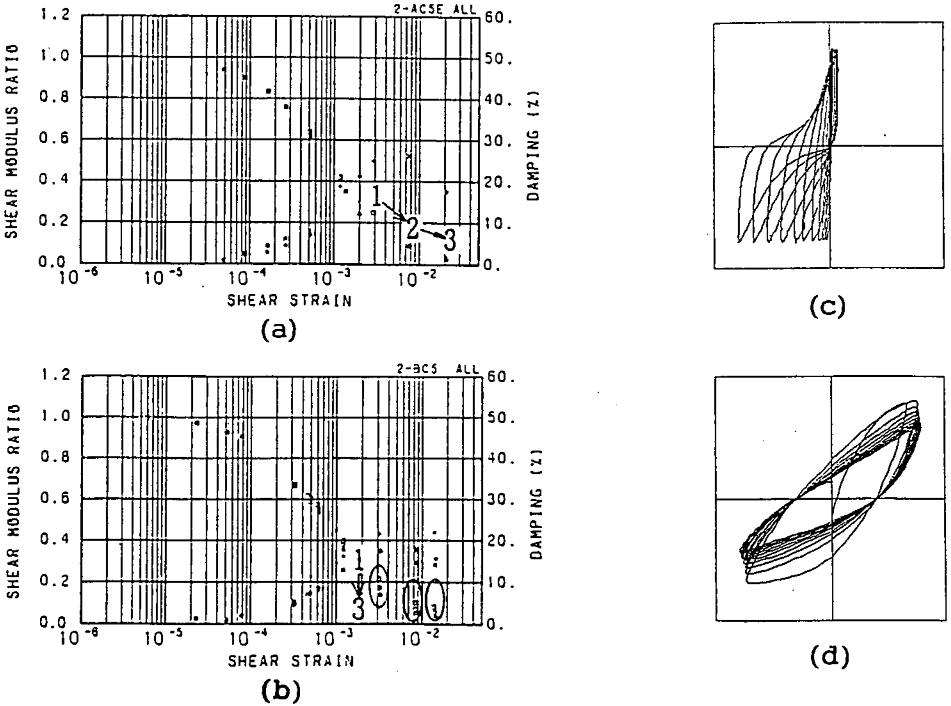
Table 1 Soil profile of Goi vertical array

| No. | Layer | H(m) | $\gamma_t$(t/m³) | $V_s$(m/sec) |
|---|---|---|---|---|
| 1 | Silty Fine Sand | 4.30 | 1.80 | 110 |
| 2 | Fine Sand | 2.80 | 1.90 | 175 |
|  |  | 4.60 | 1.90 | 210 |
| 3 | Silty Clay | 4.00 | 1.73 | 150 |
| 4 | Tuffaceous Clay | 4.80 | 1.53 | 180 |
| 5 | Clayey Sand | 2.50 | 1.84 | 230 |
| 6 | Stiff Clay | — | 1.84 | 310 |

## 2 RESULTS OF PREVIOUS STUDY

The previous study[Katayama et al;1992] can be summarized as follows:

(1)The recorded motions were calibrated of gains, filtered adequately considering the frequency characteristics of seismometers and corrected existing relative deviation of orientation of seismometers installed at near the ground surface(GL.-1m) and the underground(GL.-26m).



(a)

(c)

(b)

(d)

Fig. 1 Example strain-dependency of Layer 2; (a)by Stress-control (b)by Strain-control; (c) Hysteresis loops by stress-control (d)Hysteresis loops by strain-control.

(2)Velocity structure and unit weights of soil of the site as shown in Table 1 were determined by in-situ velocity profiling by suspended probe method and physical property tests in laboratory.

(3)The strain-dependency of the soil samples from each significant soil layer was determined by both stress-controlled and strain-controlled triaxial cyclic tests under in-situ confining pressures. Figs. 1(a) and (b) show the measured shear moduli at stress level of ca. 0.3 kg/cm$^2$ of the second soil layer(Fine sand) by the above two methods. In these figures, 1, 2, and 3 denotes the measured shear modulus at each range of 1st to 4th, 5th to 7th, and 8th to 10th cycles, of which hysteretic curves are shown in Figs. 1(c) and (d), respectively. From these figures it may be understood that the measurement of shear moduli is practically difficult and erroneous in the case of stress-controlled test; however easy and reliable in the case of strain-controlled test. The final strain-dependency of all soil layers are shown in Fig. 2(f).

(4)Using a set of ground motion records of small amplitudes in linear frequency-domain analysis, the velocity structure shown in Table 1 and the initial material damping ratio of 3% for all the soil layers were confirmed as shown in Fig. 2(e). The results of simulation analysis are respectively shown in time-history and transfer function of NS component in Figs. 2(a) and (c).

(5)The NS component of the strong ground motions recorded in the event of 1987 Off-Bousou Peninsula earthquake at GL.-1m is compared in Figs. 2(b) and (d) in time-history and transfer function with that reproduced by equivalent-linear method using the recorded motions at GL.-26m underground by assuming the fraction of 0.65 to the maximum strain and the strain-dependency shown in Fig.2(f) with the additional initial damping of 3% as previously determined. The observed motion is well reproduced.

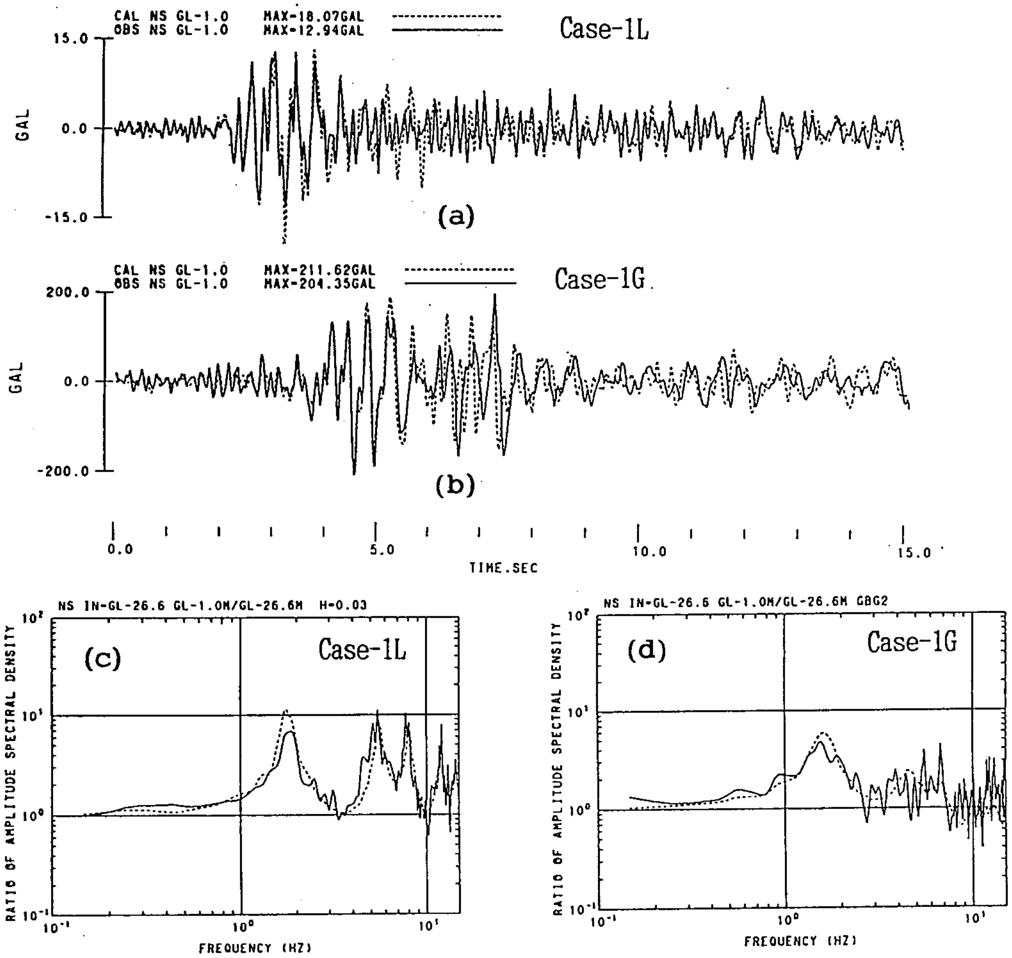
(6)As one of parametric study to examine the effect of unfavorable evaluation of soil layering model on the simulation, the velocity profile of the present model(Fig.2(e)) was simplified to consist of three layers and the standard strain-dependency curves shown in Fig.3(c) was used in the analysis. The agreement between the observed and computed motions in time-history is fairly good as a whole as is shown in Fig.3(a), if the apparent phase lag of this computed motion is neglected; however, the predicted frequency components higher than 7Hz showed larger attenuation as is shown in Fig. 3(b) than the previous case in Fig. 2(d) by the model shown in Fig. 3(d); this suggests that an arbitral simplification of velocity structure and a general strain-dependency may not result a reliable motion.

## 3 RESULTS OBTAINED AT MULTI-DEPTH ARRAY DATA

The stratigraphy and soil properties of newly introduced vertical array are summarized in Table 2. This array operated by Penta Ocean Company(PO) has installed six sets of triaxial seismometers in the six different depths but have recorded only small amplitude accelerograms yet. Because of its extensive layout of seismometers, a few sets of small amplitude acceleration records obtained at the array were used for simulation analyses to confirm the velocity structure of the site and estimate the initial damping value. The representative results are shown in Figs.4(a) through (d) in time-histories and transfer functions at selected depths in comparative form similar to the previous Fig.2. The agreement between the observed and predicted motions seems good enough to support the analysis procedure followed by us in the previous study and the necessity of the initial damping value to be introduced into linear soil response analysis. The most suitable initial damping values was similarly 3% as in the previous study.

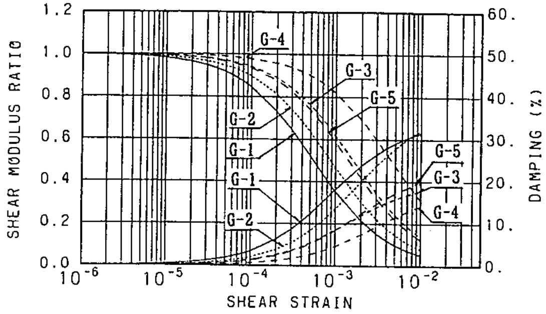
## 4 PROPOSAL OF AN APPLICATION RULE OF THE ANALYSIS METHOD

It was shown that both the linear analysis and the non-linear analysis combined with equivalent linear approach of free-field soil response by an ordinary frequency-domain method currently used are fundamentally reliable if it were



| Layer<br>GL±0 (m) | S-wave Velocity Vs (m/sec) | Unit Weight $\gamma_t$ (t/m³) | G/G₀~γ, h~γ Curve No. | |
|---|---|---|---|---|
| | | | Case-1L | Case-1G |
| Silty Fine Sand<br>GL-4.3 | 110 | 1.80 | Linear (h=3%) | G-1 |
| GL-7.1 | 175 | 1.90 | Linear (h=3%) | G-2 |
| Fine Sand<br>GL-11.7 | 210 | | | |
| Silty Clay<br>GL-15.7 | 150 | 1.73 | Linear (h=3%) | G-3 |
| Tuffaceous Clay<br>GL-20.5 | 180 | 1.53 | Linear (h=3%) | G-4 |
| Clayey Sand<br>GL-23.0 | 230 | 1.84 | Linear (h=3%) | G-5 |
| Stiff Clay<br>GL-26.6 | 310 | 1.84 | Linear (h=3%) | Linear (h=3%) |

(e)



(f)

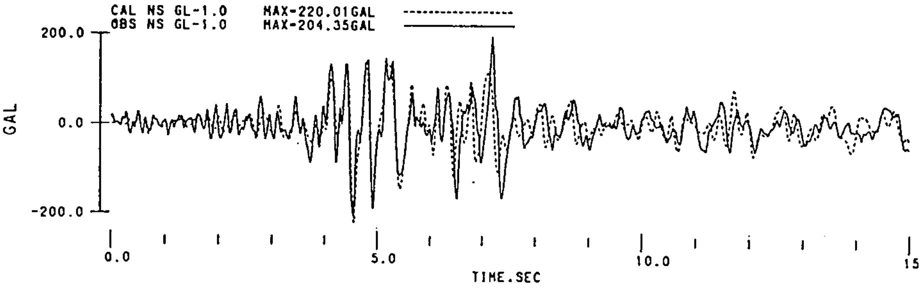
Fig.2 Simulation results of Goi vertical array: (a) Simulation of small amplitude accelerogram,(b) Simulation of 1987 Off-Bousou Peninsula Earthquake, (c) Comparison of transfer functions of (a), (d) Comparison of Transfer functions of (b), (e) Analytical model used for (a) and (b), (f) Strain-dependency of site soil layers.

supported by a careful determination of velocity profile and evaluation of damping nature of soil. Based upon this, we may propose an application rule of the ordinary one-dimensional frequency-domain wave propagation analysis by equivalent linear approach as follows:

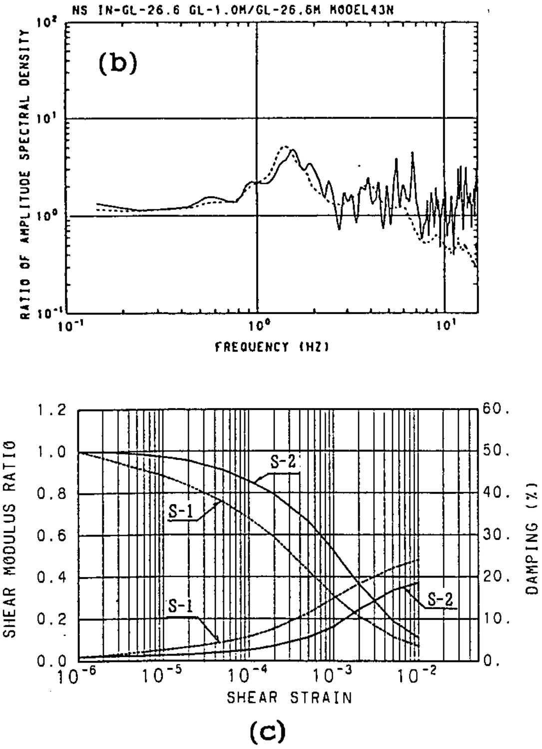
(1)The realistic velocity profile and strain-dependency of subsurface soil layers shall be collected by extensive in-situ exploration and laboratory test and be reflected on analysis as detailed as practically possible. Some modification or simplification of actual velocity structure or easy selection of strain-dependency curve may unfavorably affect the results.

(2)Since the strain-controlled test is practicable with small additional modification of available triaxial test devices and can avoid erroneous measurements of strain-dependency at high stress, strain-controlled tests are recommended.

(3)An observation using vertical array of ground motions of small amplitudes at a given site is rather easy to perform within a fairly short time period. Using the ground motions of small amplitudes recorded, the velocity structure of layered soil should be confirmed by linear analysis. Through this, some unknown attenuation capacity of soil layer at infinitely small strain can be estimated as frequency-independent initial damping.



(a)



(c)

| Layer<br>GL±0 (m) | Case-2S | | |
|---|---|---|---|
| | S-wave Velocity Vs (m/sec) | Unit Weight $\gamma_t$ (t/m³) | G/G₀~γ h~γ Curve No. |
| Silty Fine Sand<br>GL-4.3 | 110 | 1.80 | S-1 |
| Fine Sand<br>GL-11.7 | 197 | 1.90 | S-1 |
| Silty Clay<br>GL-15.7 | 180 | 1.67 | S-2 |
| Tuffaceous Clay<br>GL-20.5 | | | |
| Clayey Sand<br>GL-23.0 | | | |
| Stiff Clay<br>GL-26.6 | 310 | 1.84 | Linear (h=3%) |

(d)

Fig.3 Simulation results by simplified soil layer model:(a) Comparison of ground surface motions, (b) comparison of transfer functions, (c) Standard strain-dependency used, and (d) Simplified soil layer model.

(4)The initial damping thus obtained should be introduced into further non-linear analysis as the base damping value, on which the strain-dependent hysteretic damping characteristics obtained from laboratory tests has to be considered depending on working strain in the analysis.

## 5 REFERENCES

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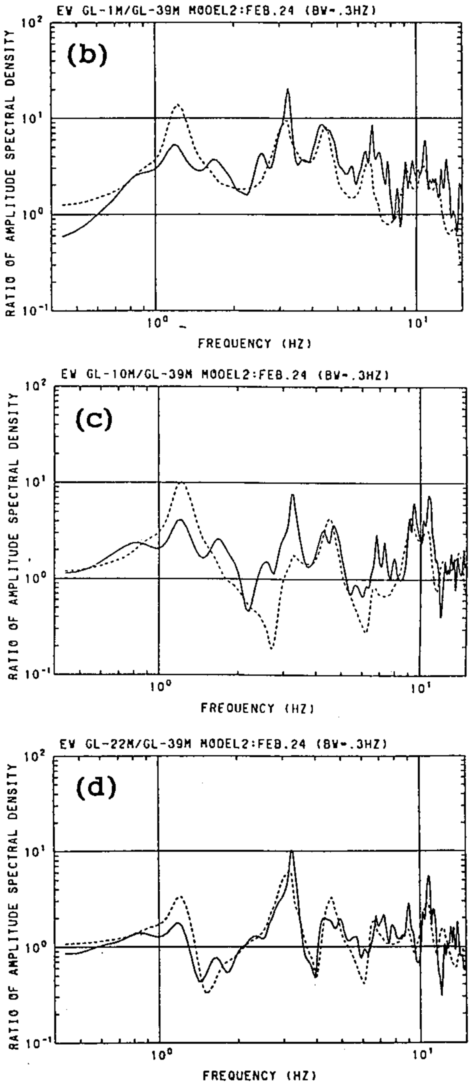
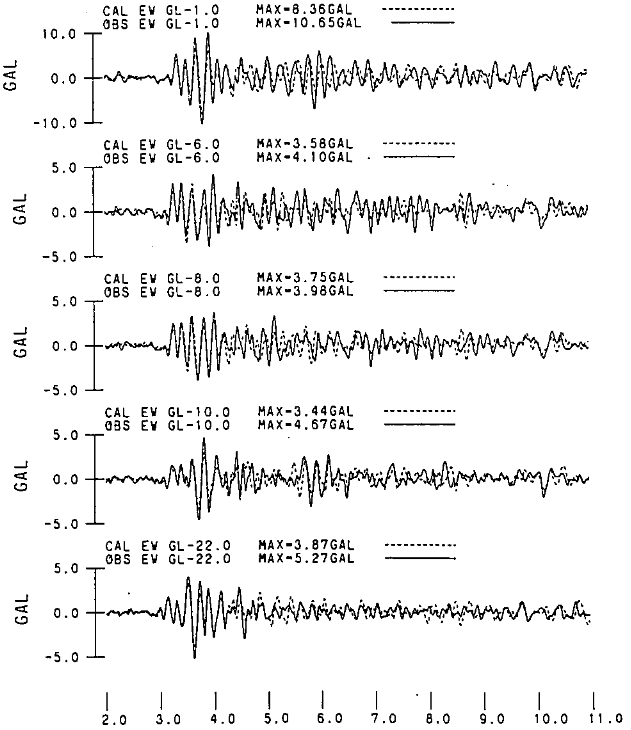
Table 2 Soil profile of PO vertical array

| No. | Layer | H(m) | $\gamma_t$(t/m$^3$) | $V_s$(m/sec) |
|---|---|---|---|---|
| 1 | Clayey Silt | 4.40 | 1.60 | 70 |
| 2 | Fine Sand | 4.25 | 1.90 | 130 |
| 3 | Silty Clay | 10.00 | 1.70 | 120 |
| 4 | Sandy Silt | 3.00 | 1.75 | 170 |
| 5 | Silty Sand | 3.80 | 1.85 | 300 |
| 6 | Clayey Silt | 5.15 | 1.65 | 220 |
| 7 | Sandy Silt | 2.00 | 1.75 | 250 |
| 8 | Silty Sand | 1.95 | 1.85 | 270 |
| 9 | Fine Sand | — | 1.95 | 300 |





(a)

Fig.4 Simulation results at PO vertical array: (a) Comparison of motions, (b)-(d) Comparison of transfer functions at three depths.