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Seismic response of soil layer and its dynamic properties

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ABSTRACT : Seismic response of deep soil ground is studied by means of a deep down-hole array with special focus on soil damping evaluated in-situ and in the laboratory. The results are then discussed in the light of other research results of recent years to identify damping characteristics in seismic response of soil layers.

1. INTRODUCTION

Seismic response of soil layers or local soil amplification due to strong earthquakes plays an important role for the seismic safety of structures. Dynamic soil properties are among the decisive factors along with soil profiles, incident wave parameters, topographical and base-rock irregularities, etc.

To investigate these effects, enormous efforts for obtaining seismic response records by installing arrays of instrumentation in soil layers are now being made in many countries. In Japan, specifically, a great number of earthquake measurement sites have been established with multi-level down-hole array instrumentation systems in subsurface soils (Working Group for Strong Motion Arrays(SMA) 1989). Most of the earthquake measurement sites have not yet experienced earthquakes stronger than the JMA intensity V, strong enough to exert the nonlinear behavior. One of the exceptions is the record during the 1980 earthquake (Tazo et al. 1987) in which the maximum acceleration of 435 cm/sec^2 was measured at the surface and 134cm $/sec^2$ at the depth of 28m below in volcanic soil layer due to a M=6.0 earthquake event.

In other countries like US and Taiwan, similar earthquake measurement sites employing the down-hole array are gradually increasing in number. In Lotung, located in a highly seismic area in the north-east of Taiwan, a comprehensive field test on the soil-structure interaction of a scaled building model has been carried out by employing a set of instrumentations including down-hole arrays in the foundation ground of saturated soft silty sand underlain by medium dense sand (Hadjian et al. 1991). In two-years term, quite a few earthquake records have been obtained including two bigger events exceeding the acceleration of 200cm/sec^2.

One of the important aims of these researches has been to identify dynamic soil properties like the shear modulus and the damping ratio to be used for evaluating seismic response.

With regard to the modulus, the shear wave velocity measured in the field normally allows satisfactory evaluation of in-situ small strain modulus. While the modulus for larger strain level can no longer be directly evaluated in the field but in the laboratory test incorporating intact soil samples, it is essential to know to what extent the strain-dependent modulus degradation measured in the laboratory test can represent the actual soil performance during strong earthquakes. A couple of research works have made valuable contributions to this issue (e.g. Hadjian et al. 1991), though lots of efforts are still to be done to draw generalized conclusions.

With respect to the damping, a larger number of issues are still unsolved largely due to difficulties of making direct field measurements of the damping ratio. Although the damping ratio corresponding to small-strain level and larger-strain level as well can be measured in the laboratory these days by means of the cyclic loading test or the resonant column test, critical review on its applicability to the field is still remained to be thoroughly studied.

By virtue of widespread installations of the down-hole array of recent years, the soil modulus and damping can now be estimated by comparing the recorded multi-level earthquake motions with numerical analyses.

In the following, a typical research effort which has been carried out very recently in Japan by incorporating deep down-hole array earthquake measurements, laboratory soil tests and numerical analyses is introduced with a

special focus on importance of the evaluation of soil damping. The findings in the research are discussed together with other recent research results to confirm the present state of knowledge.

2. SITE CHARACTERISTICS AND SOIL PROPERTIES

The array was set up in K-site in a coastal flat area about 80km east of Tokyo by drilling several boreholes in the same site to accomodate the down-hole array instrumentation at nine different levels as shown in Fig.1. The deepest hole was drilled down to 502m from the ground surface so that the Pleiocene sedimentation rock with the shear-wave velocity of

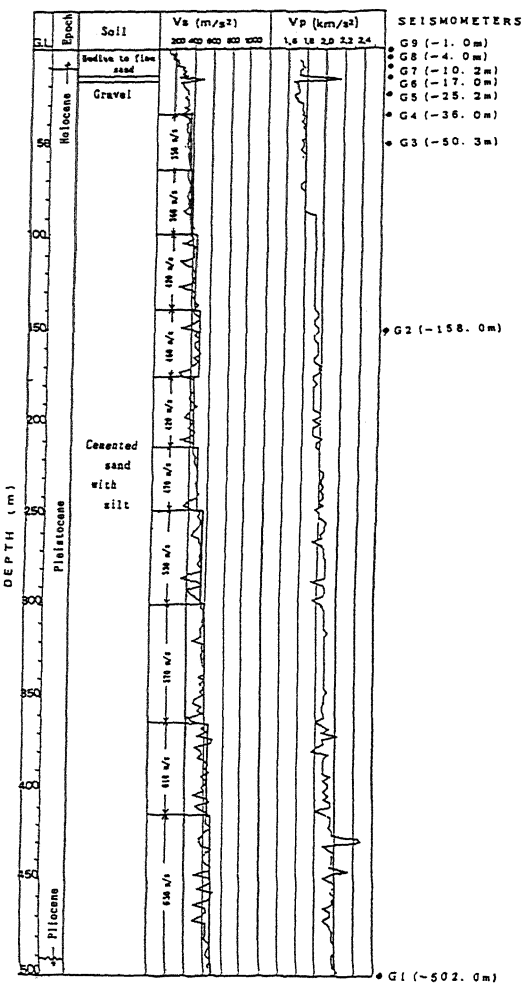

Fig.1 Boring Logging, P-S Logging and Down-hole Seismometers

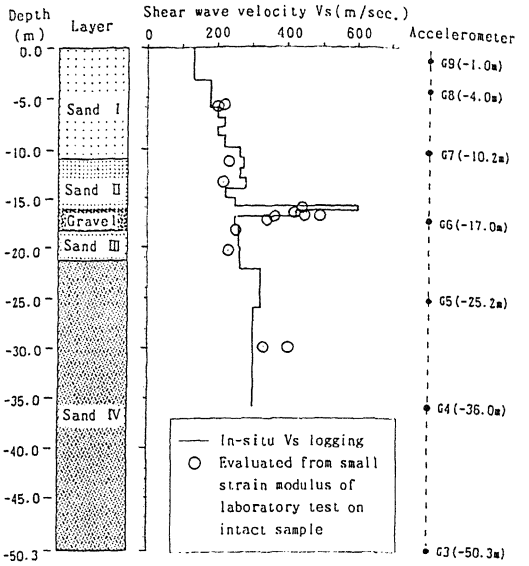

Fig.2 Shear Wave Velocity Compared with Laboratory Test Evaluation Using Intact Soil Samples.

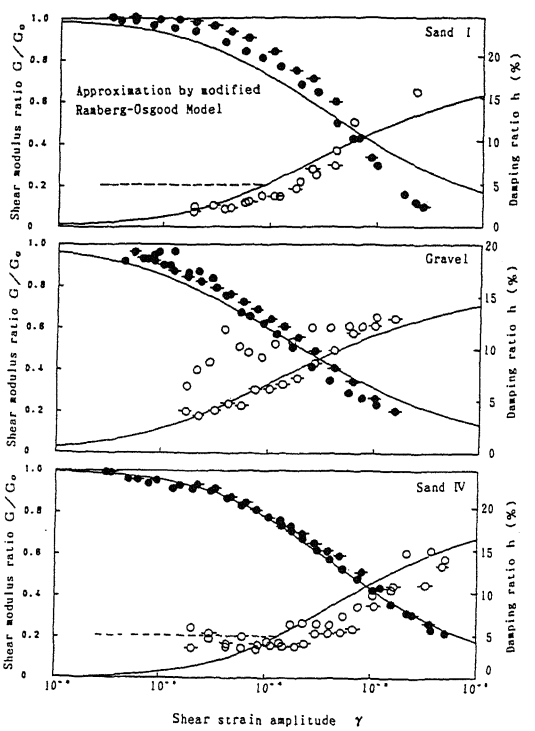

Fig.3 Variation of Shear Modulus Ratio and Damping Ratio against Shear Strain Amplitude Evaluated by Cyclic Triaxial Test

650m/sec was reached. Above the rock a rather uniform horizontal layer consisting of Pleistocene cemented fine sand of about 480m thick is resting with a thin horizontal gravelly layer of about 2.5m thick and a loose to medium sand surface layer of 16m thick capping it. The P- and S-wave velocities measured down to 502m by the PS logging method are shown in Fig.1, indicating the shear-wave velocity almost monotonically increasing with depth.

Soil sampling was executed in shallower layers to provide high-quality intact sample for laboratory tests. A triple tube sampler was employed to recover uncemented or slightly cemented fine sand down to 30m from the ground surface, whereas a refined sampling technique called as in-situ freezing sampling method was applied to the gravelly layer of 16 to 18.5m in depth. This sampling method has been developed in recent years for obtaining an intact sample of gravels of 30cm in diameter with least disturbance in micro-structure of soil due to sampling (Kokusho 1987). The samples were set in a triaxial apparatus to make a cyclic loading test under in-situ effective confining stress. In these tests an improved type of test apparatus was used in which the soil strain of the order of 10^{-5} can be reliably measured with the help of a non-contact type displacement gage (Kokusho 1980).

Small strain moduli thus measured are converted and compared with the shear wave velocity obtained by the in-situ S-wave logging as illustrated in Fig.2. A fairly good agreement in the comparison seems to indicate the reliability of the laboratory test based on the intact samples. Fig.3 shows the results of the triaxial tests in terms of the variations of the shear modulus ratio, G/Go, and the damping ratio,h, against the dynamic strain amplitude in which G and G_0 represent the shear moduli corresponding to a certain level and to an infinitely small level respectively.

3. MEASURED SEISMIC RESPONSE

Twenty five earthquake records were obtained for about two years from Dec. 1988 to Jan. 1991. Among them the largest magnitude was M=6.0 with the epicentral distance Δ=27km and the largest value of the peak horizontal acceleration at the ground surface 114cm/sec² in a M=5.2 earthquake event with Δ=43km. In Fig.4, an example of the recorded motions are shown for an event of M=4.9 and Δ=12km.

Fig.5 shows the distribution of the peak horizontal acceleration amplification along the depth with respect to the reference value at the deepest G1 point (GL.-502m) for the 25 recorded earthquakes. It is noted that the amplification factors do not increase but stay almost constant from the deepest G1 point up to the depth of 17m below the surface. Marked amplification takes place solely in the top part shallower than 17m. These amplification characteristics are quite similar in two perpendicular horizontal directions and also very stable for different earth-

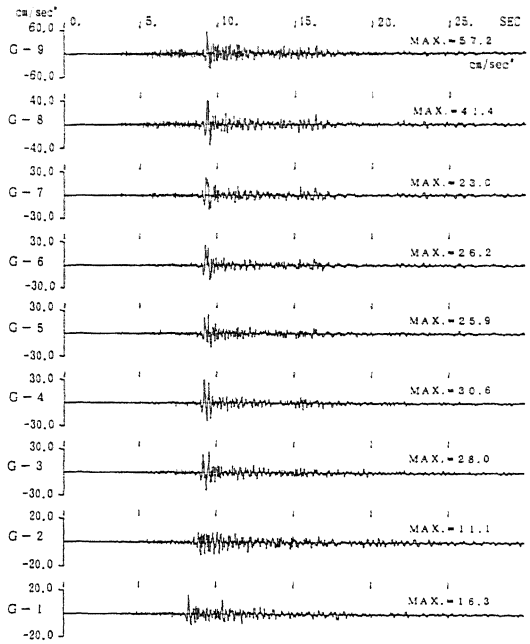

Fig.4 Typical Recorded Motions of Vertical Array (Horizontal ACC. EQ-11 N55W, M=4.9, Δ=12km)

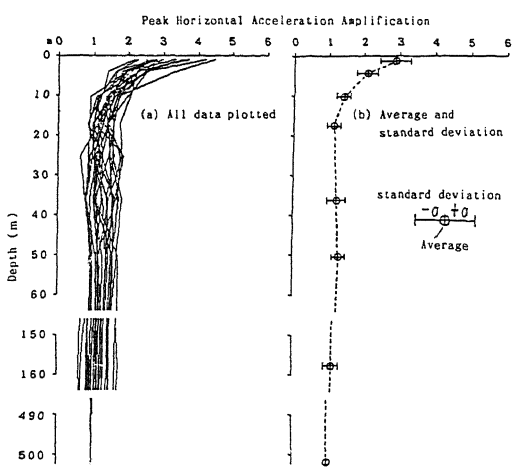

Fig.5 Distributions of Peak Horizontal Acceleration Amplification for 25 Earthquakes and their Averages

quakes with various intensities, magnitudes and epicentral distances, leading to the standard deviations of the amplification factor for the 25 earthquakes being about ±20 percent of the average value and quite stable for all the down-hole levels.

In Fig.6 the transfer functions calculated as the average of the recorded larger earthquake motions between the ground surface level G9 (GL.-1m) and the two down-hole levels, G1 (GL.-502m) and G3 (GL.-50m), are shown for the two perpendicular horizontal motions. Evidently, the functions are much the same in two orthogonal directions, indicating the soil layer in this site is quite isotropic in its dynamic response. Also remarkable is that the peak amplification factors take the values around 6 and do not change much from the lowest frequecy peak to the higher frequency peaks.

In Fig.7, the transfer functions calculated from the recorded horizontal motions between different down-hole levels are shown for two groups of earthquakes ; a larger earthquake group in which the maximum horizontal acceleration at the ground surface is larger than 50cm/sec² and a smaller earthquake group in which the maximum acceleration is smaller than 25cm/sec². The two curves are essentially the same except for the upper part of the soil layer

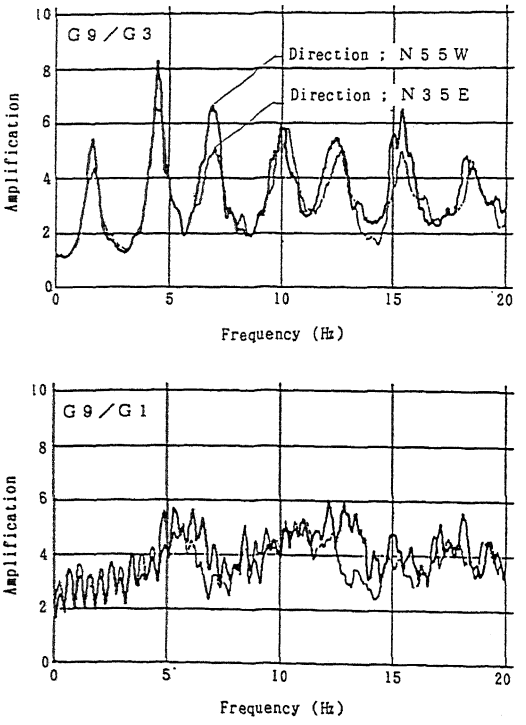

Fig.6 Transfer Functions between Ground Surface(G9) and Two Deeper Levels(G1,G3)

where peaks of the transfer function are slightly shifted toward the lower frequency for the larger earthquakes. This may indicate the effect of the nonlinear soil properties, though the effect seems minimal for earthquakes with the peak ground acceleration of about 100cm/sec² or less.

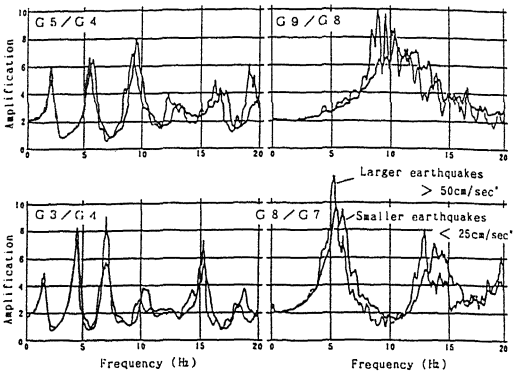

Fig.7 Transfer Functions for Larger and Smaller Earthquakes

4. ESTIMATION OF SOIL PROPERTIES BASED ON SEISMIC RESPONSE

In order to evaluate in-situ dynamic soil properties based on seismic response records, two kinds of numerical analysis were conducted by assuming the one dimensional horizontal shear wave propagation in the vertical direction. Firstly the one-dimensional seismic response analysis was carried out incorporating the soil properties based on laboratory soil tests to judge their appropriateness from the rate of the agreement between the analysis and the actual data. Secondly the inversion method was employed to numerically optimize the most probable soil properties in each layer of the soil model to reproduce the actual response with least discrepancies in response.

One Dimensional Analysis with Given Properties

Numerical analyses have been carried out to simulate the measured response by using the SHAKE program developed by Schnabel et al. (1992). The initial shear modulus for each layer was determined based on the measured in-situ shear wave velocity, whereas the strain-dependent changes of the shear modulus and the damping ratio were given on the basis of the Ramberg-Osgood Model with its parameters most appropriate for the laboratory test data as indicated with the solid curve in Fig.3 (Tohma et al. 1992). The measured motion at the depth of 50.3m was given to the model and the motions of the upper layers were calculated.

Fig.8 exemplifies the vertical distribution of the computed maximum horizontal acceleration compared with the measured values as well as the distributions of the maximum shear stress and the maximum shear strain for a larger seismic motion recorded in the site. The dotted curve in the graph corresponds to the case in which the strain-dependency of the damping ratio, h, is modified so that the lowest value of h is fixed as 5% as shown in Fig.3 on the ground that, as later described, the seismic records optimization evaluates the damping ratio of the sand layers as about 5%.

The transfer functions between G9 (near the surface) and G3 (GL.-50.3m) for the same earthquake motion is shown in Fig.9, which indicate that the computed transfer function using the damping ratio with the lower limit of 5 percent tends to give a slightly better agreement with the actual response in comparison with the damping ratio which approaches zero with decreasing strain level. However, there exists a striking difference between the actual and computed responses irrespetive of the damping values in that the peak amplitudes in the transfer function of the SHAKE analysis tend to monotonically decline for higher frequency while those of the actual response stay at almost the same level. This may imply the hysteretic damping incorporated in the SHAKE analysis may not appropriately represent the actual damping mechanism exerted in the small strain oscillation.

Tohma et al.(1992) has demonstrated that the introduction of the Maxwell type damping in which the damping ratio adversely proportional to the frequency will considerably improve the reproduction of the transfer function. Similar findings have been reported by several researchers who made comparative studies of earthquake motions between different down-hole levels.

On the other hand, in order to estimate the damping ratio exerted in deeper soil layers based on the measured data, the SHAKE analysis was performed for the soil model with the shear wave velocities of the deeper layers as shown in Fig.1. The measured motion was given at the depth of G3 (GL.-50.3m) and the computed results at G2 (GL.-158m) and at G1 (GL.-502m) were compared with the respective recorded motions. Fig.10 shows the comparison of maximum accelerations in which the damping ratio for all the soil layers deeper than 50.3m is varied in three steps ; 2.0%, 1.0%, and 0.5%.

This obviously indicates the appropriateness of damping ratio as low as 0.5% for the deep layer from GL.-158m to GL.-502m. It may also be said that for the layer from GL.-50.3m to GL.-158m a slightly higher damping ratio as 2% is probable. Considering that still higher damping ratios are evaluated for the soil layers shallower than

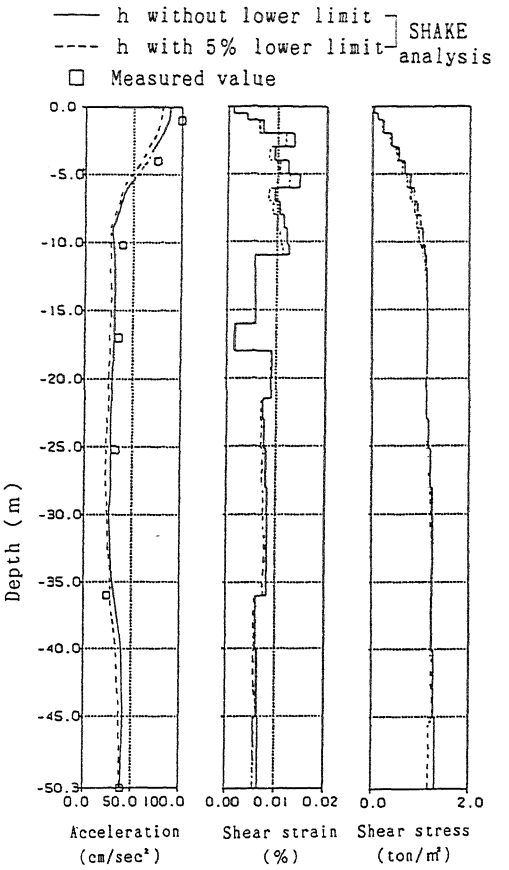

Fig.8 Distributions of Max. Values Computed by SHAKE Analysis (EQ-8, N55W)

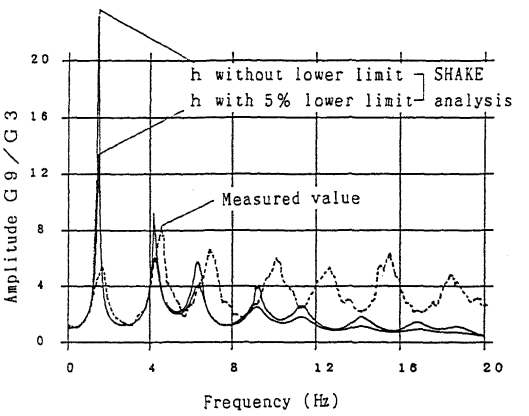

Fig.9 Transfer Functions (G9/G3) Compared between Analysis and Measurement (EQ-8, N55W)

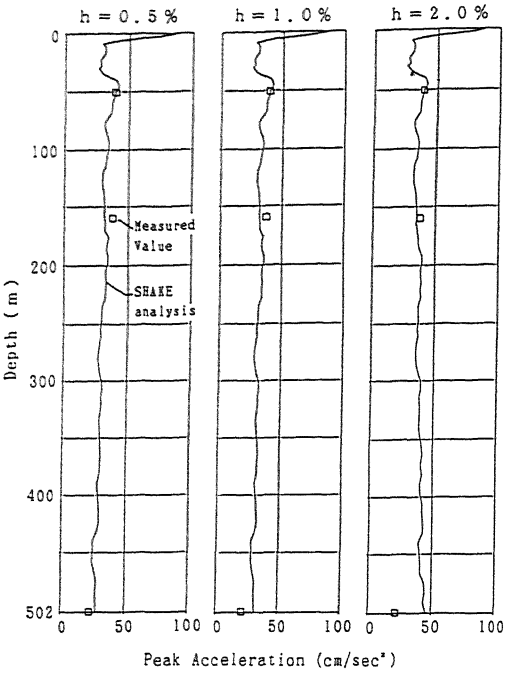

Fig.10 Peak Accelerations in Deeper Layer Estimated by SHAKE Analysis with Different Damping Ratios (EQ-8, N55W)

GL.-50.3m, it may be concluded that the damping ratio of soil is very dependent on the depth.

Optimization by Inversion Method

Based on horizontal motion records with the maximum surface acceleration exceeding 50cm/sec², the shear wave velocities and the damping ratios of the soil layers were analytically evaluated by means of the inversion method (Ishida 1987). This calculation was implemented for the soil layers above the G3 point (GL.-50.3m) where the seismometers are densely instrumented. The soil model was set up with the initial estimates on soil properties as shown with the broken lines in Fig.11 based on the S-wave logging results and initial guess on damping. Then the inversion was carried out iteratively to attain the best fitting between observed motions and analytical ones.

The converged results for seven different motions are together shown in Fig.11. It is evidently seen that the optimized shear wave velocity does not very much differ from the initial value on the whole. This may readily be understood from the fact that the maximum shear strain exerted in the ground during these earthquakes is estimated as 2×10^{-4} at the largest based on the analytical results indicated in Fig.8.

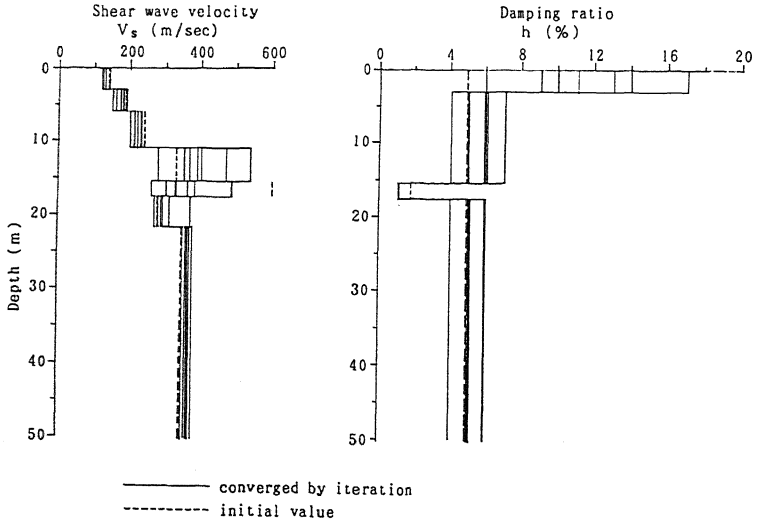

Fig.11 Estimation of Shear Wave Velocity and Damping Ratio by Optimization Method for 7 Recorded Motions

The damping ratio, by using a simpler four-layered model because of the technical reasons in computation, is optimized as around 5 or 6 percent for the most soil deeper than 3m. The damping ratio of 1 percent for the gravelly layer seems too small and unreliable considering the thickness of the layer is too thin to be reliably computed. Instead, the optimized value shoud be interpreted almost the same as the sand layers sandwiching the gravel layer. While these values are not so much different from the initial guess, the damping ratio in the top layer is remarkably larger as 6 to 17 percent. Despite some computational problems the results may contain, this appears to qualitatively reflect the actual performance of the soil that a larger damping is locally exerted in a surface soil where the confining stress is very small.

5. DAMPING RATIO OF IN-SITU AND LABORATORY

The damping ratio though difficult to evaluate in the field have been estimated by several Japanese researchers for various soils covering soft rock to soft clay based on the down-hole seismic survey, the vibrator test and the optimization of earthquake records corresponding to the soil depth of less than 50m and the strain level of 10^{-4} or less as tabulated by Kokusho (1987). In Fig.12 these damping values are grouped for similar soil kinds and shown as probable intervals of the in-situ damping ratio. Evidently softer soils like alluvial clays and silts appear to have smaller damping ratio than stiff soils like gravel and soft rock, and sands tend to have a wide range of values in the middle.

On the other hand, Fig.13 summarizes the damping values and their strain-dependent variation for various soils (Kokusho 1987) measured in the laboratory by Japanese researchers. It is noteworthy that the laboratory damping values seem to be basically in accordance with the in-situ values indicated in Fig.12. It is also of interest that there are some soil materials which exhibit very high damping ratio under relatively low confining stress and that soft rock, different from the damping values indicated in Fig.12, can have relatively small damping ratio under high confining stress.

In TABLE-1, some of damping ratios more recently evaluated in the field by Japanese researchers are listed which include the values corresponding to very deep ground reaching one thousand meter or more. Also noted are the two research results (Tazo et al. 1987 and Suetomi et al. 1990) which have highlighted the strain dependent increase of the damping ratio during strong earthquakes.

In Fig.14, in-situ damping ratios are compared with damping ratios measured in the laboratory on intact samples recovered from corresponding

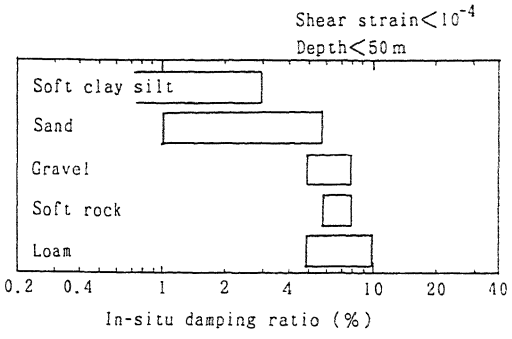

Fig.12 Damping Ratio Estimated In-situ for Various Soils

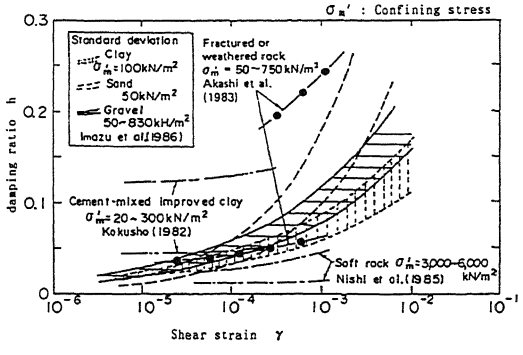

Fig.13 Damping Ratio vs. Shear Strain Relationship for Various Soils obtained from Numerous Laboratory Test Results

TABLE 1 Damping Ratios of Various Soil/Rock Recently Evaluated in the Field by Japanese Researchers

Damping Ratio (%)	Soil/Rock	Shear wave velocity (m/sec)	Depth	Evaluation method
2~4 1 0.3	Sandy loam Sandy soft rock Schist	450 700~900 2500	0~350 350~1200 1500~	S-wave logging Yamamizu et al.(1986)
2~6 1~4 3~6	Sand stone Silty sand stone Sand stone/ Granite rock	520 700~1200 1200~2800	0~100 100~600 600~1000	EQ down-hole records optimization Ishida et al.(1987)
2~3 [11~13]*	Loam/Scoria	125~800	0~28	EQ down-hole records optimization (for f=0~2Hz) Tazo et al.(1987)
10~14 [18~21]** 4~5 [8~13]** 4~5 [9]** 3 [4]**	Loam stiff sandy clay Fine sand Fine sand	140 320 320 420	0~5 5~10 10~20 20~36	EQ down-hole records optimization (for f=1 Hz) Suetomi et al.(1990)

Note : Soil strain is in the order of 10^{-4} or less, except for
* : corresponding to max. surface Acc. ≒435 cm/sec²
** : corresponding to max. surface Acc. ≒300 cm/sec²

depths in the same site. Though such data are still scarce in number it is obviously seen that the damping ratios are in most cases evaluated larger in-situ than in the laboratory. The specific reason for Sand I in K-site may seemingly be attributed to the very shallow depth (3m from the surface) of the sand layer where the confining stress is immensely low. The discrepancy is particularly conspicuous in deeper rock too where the earthquake record optimization tends to give several percent of the damping ratio in sharp contrast to one percent or less in laboratory tests.

In Fig.15 the damping ratios evaluated in-situ are plotted against the depth on the full logarithmic graph. A remarkable decrease in the damping ratio with increasing depth is quite evident despite rather large scatter of data. Though the data include a variety of soils or rocks, the effect of depth tends to overwhelm other effects if such a wide range of depth is concerned. Quite reasonably, the very large damping values near the ground surface obtained in K-site may be justified as an extreme value obtained by extrapolating the depth-dependent change. It is noted again that laboratory test data plotted in the same figure are obviously smaller than the in-situ evaluation for the same depth. According to laboratory test results under ultra-low confining stress (e.g. Kokusho 1982), the damping ratio of clean sand cannot be so large as to exceed 5 percent, thus being unable to explain the in-situ high damping ratio.

Thus, recent researches indicate that the in-situ and laboratory damping values more often differ than coincide presumably because both in-situ and laboratory evaluations of damping have their own problems and limitations.

There are several possible causes for the difference in both in-situ and laboratory evaluations. For the optimization method frequently incorporated in recent researches for in-situ evaluation, besides problems involved in the optimization scheme, the quality of referred wave motions have a decisive influence in that motions contaminated by waves other than vertically propagating body wave may lead to erroneous evaluation.

For the laboratory evaluation, the greatest limitation is that soil samples can represent only elements of a grobal soil layer. The quality of samples is another problem although its effect on damping evaluation may not be so serious as that on modulus evaluation (Kokusho 1987).

It has also been pointed out that the difference is not only for the absolute value but for its frequency-dependent variation. It has been repeatedly shown in many laboratory tests that soil damping is essentially of hysteretic

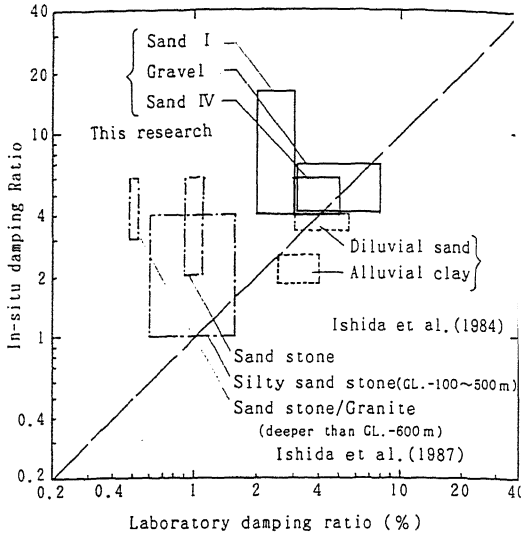

Fig.14 In-situ Damping Ratio Compared with Laboratory Value Based on Sampled Soil

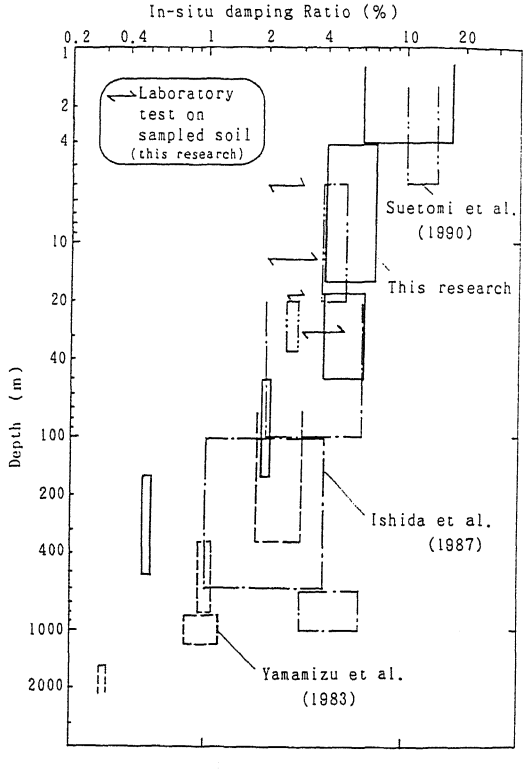

Fig.15 Variation of Damping Ratio Evaluated In-situ at Different Depth

nature and almost independent of frequency. On the other hand a majority of in-situ damping evaluations by optimizing multi-level earthquake records indicates the damping is of the frequency-dependent Maxwell type.

As one of the probable explanations to fill the gap, some researchers have recently found that a numerical model of soil layers in which finer variations of wave velocities are introduced tends to better reproduce actual behavior than a simpler model with average wave velocities.

Among them, Suetomi et al.(1991) demonstrated that the introduction of finer variation in shear modulus into a two-dimentional FEM soil model results in an equivalent effect of the introduction of the Maxwell type frequency -dependent damping ratio and that, as the hysteretic damping incorporated in the model getting larger, the Maxwell type damping characteristics will subside in the seismic response. In the writers' opinion, these researches suggest a possibility that higher frequency motions amplified by local fluctuations in shear modulus lead to the evaluation of apparantly smaller damping ratio for higher frequency, for which the soil material damping in its strict meaning is by no means responsible.

While these discussions on the soil damping for small strain level may seem to be trivial from engineering point of view, it really makes a big difference in seismic response evaluation if long distance wave propagation in deep soil layers is involved in the evaluation. In the same context, the damping ratio in the deep soil is really an important issue to be further investigated.

6. CONCLUSIVE REMARKS

Some of the findings obtained in recent researches on the effects of dynamic soil properties on seismic soil response may be summarized with special emphasis on the soil damping as follows ;

a. The damping ratio evaluated in the field is likely to have very large values near the ground surface though laboratory tests under low confining stress seemingly can not fully explain this.
b. On the contrary it appears to decrease even to less than one percent in the soil layer deeper than a few hundred meters despite rather large scatter in the evaluation.
c. Thus the depth of soil seems to be quite influencial on soil damping.
d. In contrast to laboratory test results, in -situ soil damping exerted in seismic response in small strain level earthquake does not appear to be of hysteretic type but frequency-dependent Maxwell type. Recent research results suggest that small fluctuations of shear modulus normally neglected in modelling soil layers may possibly have some effect on the apparent difference in damping mechanism between the field and the laboratory.

Certainly, more investigations are still needed for better understanding of dynamic soil properties particularly soil damping in the following respects.

a. Clarification of the damping mechanism in general for small strain level.
b. Critical review on the evaluation and interpretation methods of soil damping both in the field and in the laboratory.
c. Reliable evaluation of soil damping exerted both in deep and very shallow soil layers.
d. In-situ evaluation of soil damping exerted in various soils during strong earthquakes to be compared with hysteretic damping models.

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REFERENCES

Akashi,R., Nagatsu,T., Eto,Y., et al. 1983, Dynamic deformation properties of fractured zone materials, 18th Annual Convention of Japanese Society of SMFE, pp.497-500 (in Japanese).

Hadjian,A.H., Tseng,W.S., Chang,C.Y., Anderson, D., Tsai,N.C., Tang,Y.K. and Stepp,J.C., The learning from the large scale Lotung soil -structure interation experiments, Proc. Second Intern. Conf. on Recent Advances in Geotechnical Earthquake Eng. and Soil Dynamics, Vol.Ⅲ, pp.46-70.

Imazu,M. and Fukutake,K. 1986, Dynamic shear modulus and damping of gravel materials, Proc. 21st Annual Covention of Japanese Society of SMFE. Vol.1, pp.509-512 (in Japanese).

Ishida,H., Ohta,T., Hara,A. and Takahashi,K. 1987, Evaluation of damping factor based on laboratory experiments, S-wave logging and Seismic waves, Proc, 15th Seismic Ground Motion Symp. on Damping Evaluation in Earthquake Ground Motion, Archtectual Institute of Japan. pp.17-24 (in Japanese).

Ishida,K. 1987, Effect of the surface layer of the ground on seismic motion of the ground -Estimaton of soil profile of soft ground based on seismic observation, A Special Workshop on SMART-1 Strong Motion-Array and Lotung Large Scale Seismic Test Program, Taiwan.

Kokusho,T. 1980, Cyclic triaxial test of

dynamic soil properties for wide strain range, Soils and Foundations, Vol.20, No.2, pp.45-60.
Kokusho,T. 1982, Dynamic properties of soil and nonlinear seismic response of ground, General Report No.301, Central Research Institute of Electric Power Industry (in Japanese).
Kokusho,T. 1987, In-situ dynamic soil properties and their evaluations, Proc. 8th Asian Regional Conference on SMFE, ICSMFE, Vol.2, pp.215-240.
Nishi,K., Esashi,Y. and Kokusho,T. 1985, Dynamic strength-deformation properties of soft rocks during cyclic loading, Report No. 383050, Central Research Institute of Electric Power Industry (in Japanese).
Schnabel,P.B., Lysmer,J. and Seed,H.B. 1972, SHAKE-a computer program for earthquake response analysis of horizontally layered sites,EERC72-12, Univ. of California.
Suetomi,I. and Nakamura,S. 1990, Q value in soil deposits during earthquake, Proc. 5th Japan Earthquake Eng. Symp. Vol.1, pp.589-594 (in Japanese).
Suetomi,I. and Nakamura,S. 1991, A consideration on the effect of soil properties inhomogeniety on seimic respone of soil, Proc. 21st Earthquake Eng. Symp., Japan Society of Civil Engineers, pp.97-100 (in Japanese).
Tazo,T., Sato,M. and Hatakeyama,A. 1987, Nonlinear response analysis of soil layer based on strong seismic records, Proc. 19th Earthquake Eng. Symp., Japan Society of Civil Engineers, pp.101-104, (in Japanese).
Tohma,J., Yajima,H., Kanatani,M. and Iwatate,T. 1992, Response characteristics of thick sedimentary layers based on the deep vertical array observation, Proc.Intern. Symp. on the effects of Surface Geology on Seismic Motion, pp.299-304.
Working Group for strong Motion Arrays (SMA) 1989, Reaearch report on development of a database for strong motion array records, Earthquake Engineering Committee, Japan Society of Civil Engineers.
Yamamizu,F., Goto,N., Ohta,Y., Takahashi,H. 1983, Attenuation of shear waves in deep soil deposits as revealed by down-hole measurements in the 2,300meter-borehole of the Shimohsa Observatory, Japan Journal of Physics of the Earth, Vol.31, No.2.