SECTION 9
ESTIMATION OF SOIL STRAIN

We have obtained relatively good agreement between the observed peak values of motions and the predicted values from the proposed model. The best agreement was found for peak velocity. This motivates us to apply it to the estimation of soil strain which is associated with peak velocity. In this section, a simplified method for estimating soil strain is presented together with comparisons between predicted and observed values.

9.1 Simplified Method for Estimating Soil Strain

Soil strains induced during earthquakes have been known to play a pivotal role not only in controlling non-linear behavior of ground motions including liquefaction of sandy soils but also in determining the seismic performance of buried pipelines. Despite such importance, there have been relatively few observations of soil strain because of the technical difficulties involved. Hence it is almost impossible at present to derive an empirical expression for soil strain using the technique described previously for strong-motion peaks. However, since strain is theoretically proportional to the corresponding particle velocity, it is possible to indirectly estimate maximum soil strain using our semi-empirical model for peak velocity. According to wave theory for one dimensional propagation, the maximum horizontal soil strain ε_{max} , in the direction of propagation, is given by

$$\varepsilon_{max} = \frac{v_{max}}{C} \tag{9.1}$$

where v_{max} is the peak particle velocity, and **C** is the apparent propagation velocity of the wave with respect to the ground surface .

The term v_{max} in Eq. (9.1), needless to say, can be calculated for a site if the soil profile is known, using our semi-empirical model. We now consider methods to approximate the apparent propagation velocity **C.**

The apparent propagation velocity **C** is a function of the wave type. In the case of body waves, the apparent velocity is a function of angle of incidence and material properties of the surface soils. O'Rourke et al.[37] studied the apparent horizontal propagation velocity of S-wave using theoretical analysis as well as observed values in the U.S.and Japan. They concluded that it falls in the range of **2.0** to **5.0** km/sec with an average of about **3.5** km/sec. Since they studied a number of different sites, the average velocity of **3.5** km/sec would be acceptable as a first-approximation. Herein we employ the value of **3.5** km/sec as the apparent propagation velocity of body waves with respect to the ground surface.

For the case of surface waves, Rayleigh wave(R-wave) induces soil strain alternating between tension and compression in the direction of propagation. For R-waves, the propagation velocity is a function of frequency. This relation is quantified by a dispersion curve for the phase or propagation velocity. For typical soil profiles with shear wave velocity increasing with depth, the propagation velocity is an increasing function of period. For example, Fig.9-1 shows an approximate dispersion curve developed by O'Rourke et al.[38] for the fundamental R-wave for a uniform soil layer over a half space. For long period motion $hf/c_L \leq 0.25$, the phase velocity is somewhat less than the shear wave velocity of the half space, while for short period motion $hf/c_L \geq 0.5$, the phase velocity is equal to the shear wave velocity of the surface layer, C_L. Note however that the R-wave phase velocity corresponding to the natural frequency of the soil layer in shear $f = C_L/4h$ is $\mathbf{0.875C_H}$, that is, it is controlled by the shear wave velocity of the half space. For sites subject to both body and surface waves, we assume herein that the peak particle velocity $\mathbf{v_{max}}$ occurs during the later arriving R-wave portion of the record. We further assume that the predominant frequency of the R-wave portion matches the natural frequency of soil layer in shear. That is, for sites subject to surface waves

$$\varepsilon_{max} = \frac{v_{max}}{0.875 \cdot C_H} \tag{9.2}$$

where $\mathbf{v_{max}}$ is the peak particle velocity from Eq.(5.3) or Eq.(5.4)) and $\mathbf{C_H}$ is the shear wave velocity of the seismic bed rock which underlies the site. Based upon the reference site and the seismic bed rock for peak velocity in section 5.1, we choose 2.0 km/sec as a representative value for $\mathbf{C_H}$.

The above considerations gives us a simplified way to estimate the maximum longitudinal or normal strain separately for body waves and surface waves. The next problem is to identify which wave type is likely to be most prominent in a given record. This complicated phenomenon has been studied by several workers. In general a large earthquake with a shallow focal depth is more likely to generate surface waves. Since the detailed consideration about this problem is beyond the scope of this report and our target is to develop a simplified method for estimating the maximum soil strain, the discussion is herein confined to an assumption of surface wave generation suggested by Nakamura[39]. Nakamura[39] investigated the existence of surface waves in

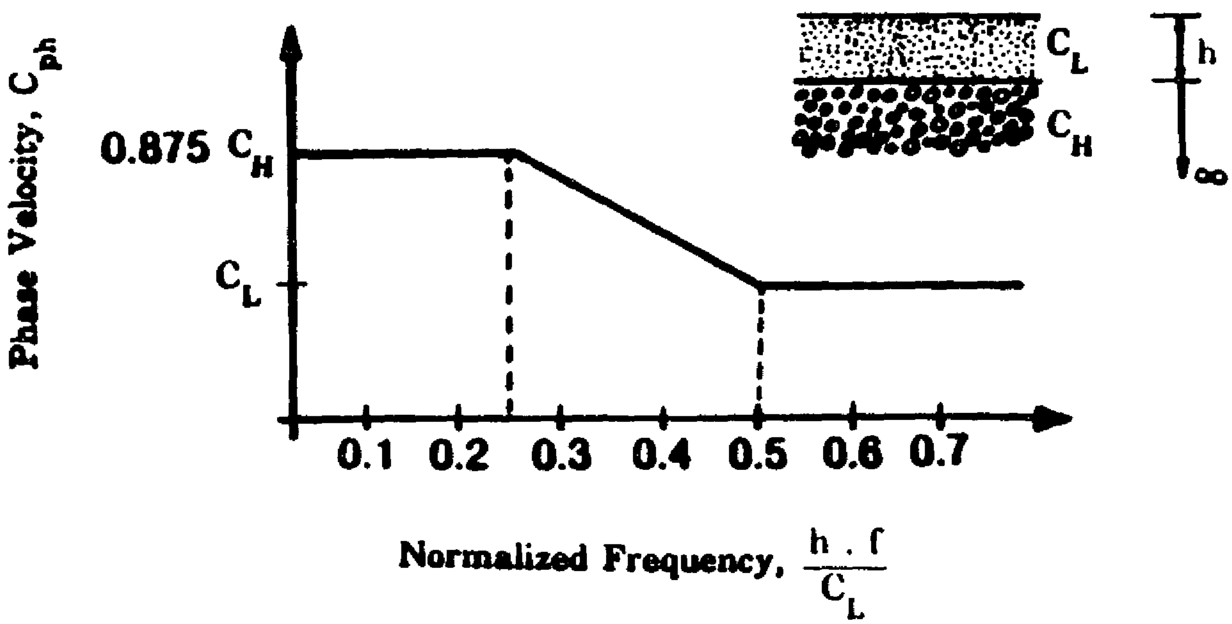

Fig.9-1 Approximate Dispersion Curve for Fundamental R-wave for Uniform Soil Layer over a Half Space(after O'Rourke et al.[38])

records obtained during a total of 29 earthquakes by the use of non-stationary spectra analysis. A table in that work identifies the generation of surface waves as being dependent on earthquake magnitude and an apparent angle defined by focal depth and epicentral distance. From the Nakamura table, we herein establish the following conditions for generation of surface waves:

$$M > 6.0 \quad \text{and} \quad \frac{\Delta}{D} > 1.5,$$

$$6.0 \geq M > 5.0 \quad \text{and} \quad \frac{\Delta}{D} > 6.0$$

where **M** is the earthquake magnitude, **Δ** is the epicentral distance and **D** is the focal depth. It should be noted that the above standard for surface wave generation is an approximation. Hence our simplified method for estimating the maximum soil strain can be summarized as follows;
For sites subject to surface waves, that is $M > 6.0$ and $\Delta/D > 1.5$, or $6.0 \geq M > 5.0$ and $\Delta/D > 6.0$

$$\varepsilon_{max} = \frac{v_{max}}{1.75 \times 10^5} \tag{9.3}$$

while for all other sites, body waves control and

$$\varepsilon_{max} = \frac{v_{max}}{3.5 \times 10^5} \tag{9.4}$$

where $\mathbf{v_{max}}$ is the peak particle velocity in cm/sec given by Eq.(5.3) or Eq.(5.4).

Eqs.(9.3) and (9.4) make it possible to estimate the maximum strain at a site provided that earthquake magnitude, epicentral distance, focal depth and hypocentral distance are known as well as the surface profile. For example, Fig.9-2 is a plot of the attenuation of estimated maximum strain at a rock site, for which $\mathbf{AMP_i(v)}$ is taken as **1.0** in Eq.(5.3) or Eq.(5.4), subject to surface waves.

9.2 Comparison of Estimated Soil Strain with Observed Values

In this section, the estimated strains given by Eq.(9.3) or Eq.(9.4) are compared with strains observed at representative sites to check the validity of the simplified method.
The Kubota Corp. in Japan has been observing soil strains as well as the behavior of pipelines during earthquakes at two separate sites in Aomori Prefecture, namely Kansen and Shimonaga.

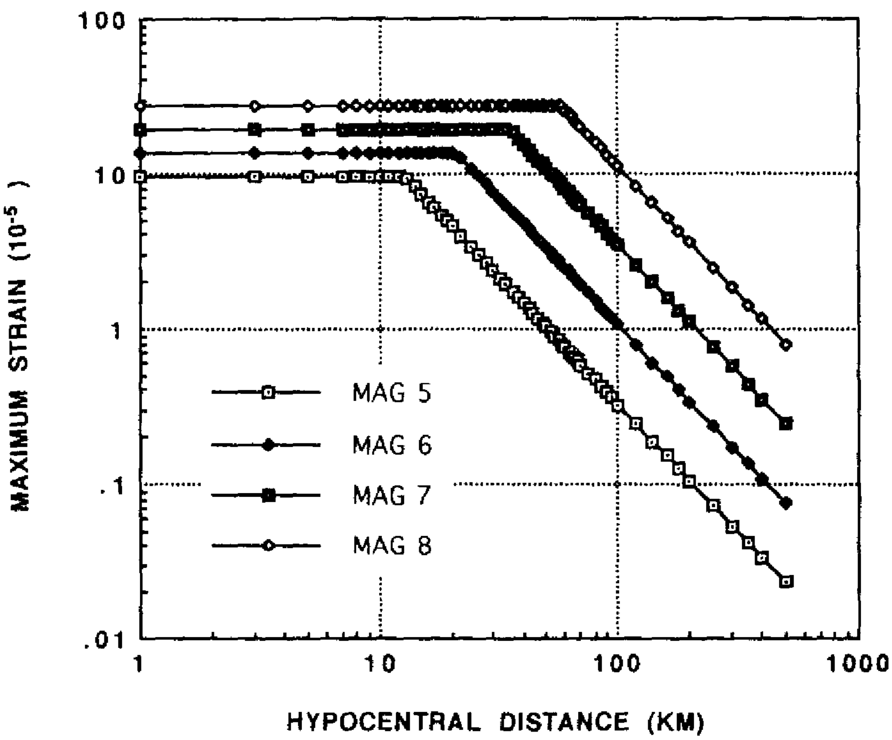

Fig.9-2 Attenuation for Estimated Maximum Soil Strain at Rock Site Subject to Surface Waves

The details of these observation systems including soil profiles at both sites are available in Iwamoto et al.[40]. Figs 9-3 and 9-4 each show the soil logs at the Kansen and Shimonaga sites. Although the observations at both sites have been carried out since 1975 giving useful data relevant to seismic performance of buried pipelines, the maximum soil strains observed until 1983 are compared with estimated normal strains from Eq.(9.3) or Eq.(9.4).

In order to estimate the maximum soil strain based on Eq.(9.3) or Eq.(9.4), one needs the amplification coefficient $\mathbf{AMP_i(v)}$ applicable to both the Kansen and Shimonaga sites. We offered two methods: the "qualitative method" and "quantitative method" for the estimate of $\mathbf{AMP_i(v)}$ at a site not included in our statistical analysis. According to the qualitative method, the value of $\mathbf{AMP_i(v)}$ at the Kansen site is expected to be about **2.70** since the Kansen soil profile in Fig.9-3 is most similar to the Itajima site in Fig. 5-13(l). On the other hand, the estimated $\mathbf{AMP_i(v)}$ by the quantitative method which consists of Eq.(5.8) and Eq.(5.9) is **2.18** because the value of $\mathbf{C_{amp}}$ is **8.30** by Eq.(5.8). The calculation of C_{amp} for the Kansen site is shown in Appendix B. This example shows that the qualitative method gives fairly accurate amplification factor, although it is simple. Since the quantitative method is expected to yield the more accurate value, we use **2.18** as the amplification factor for the Kansen site. Similarly, the quantitative method resulted in $\mathbf{AMP_i(v) = 5.28}$ at the Shimonaga site via $\mathbf{C_{amp}=35.9}$. Having obtained the amplification factors $\mathbf{AMP_i(v)}$ at both sites, it is possible to predict the maximum soil strains expected at both sites knowning the earthquake magnitude, epicentral distance, focal depth and hypocentral distance. The predicted maximum soil strains at the Kansen and Shimonaga sites are plotted, respectively, in Figs.9-5 and 9-6 and compared with observed maximum normal or longitudinal soil strains. In both figures, data points with an open circle are estimated values using Eq.(9.3) (surface wave source) while the closed circle indicates values from Eq.(9.4) (only body wave source). Fig.9-5 and 9-6 show that the predicted values coincide relatively well with the observed values. Comparisons similar to Figs.9-5 and 9-6 between the predicted and observed maximum strains are shown in Figs. 9-7 and 9-8 for two other observation sites. These are University of Tokyo, Chiba site[41] and Chubu Electrical Power Corp., Chubu site[42]. The observed strain at the Chiba site was obtained by observing pipe strain[41] and herein we assume that the pipe strain represents soil strain. Again Figs.9-7 and 9-8 show that the comparison between predicted and observed strains is relatively good.

9.3 Discussion of Simplified Method for Soil Strain

As shown in Figs.9-5 through 9-8, on average the simplified method predicts well the observed maximum normal or longitudinal soil strains. However there is some scatter between observed

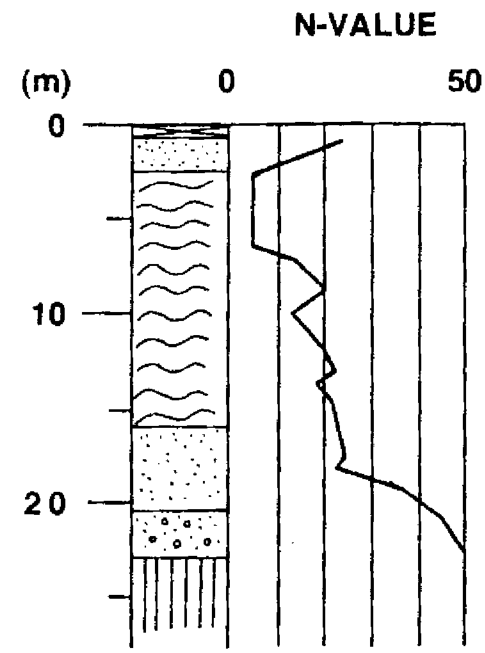

Fig.9-3 Soil Profile for the Kansen Site (Kubota Corp. Soil Strain Installation)

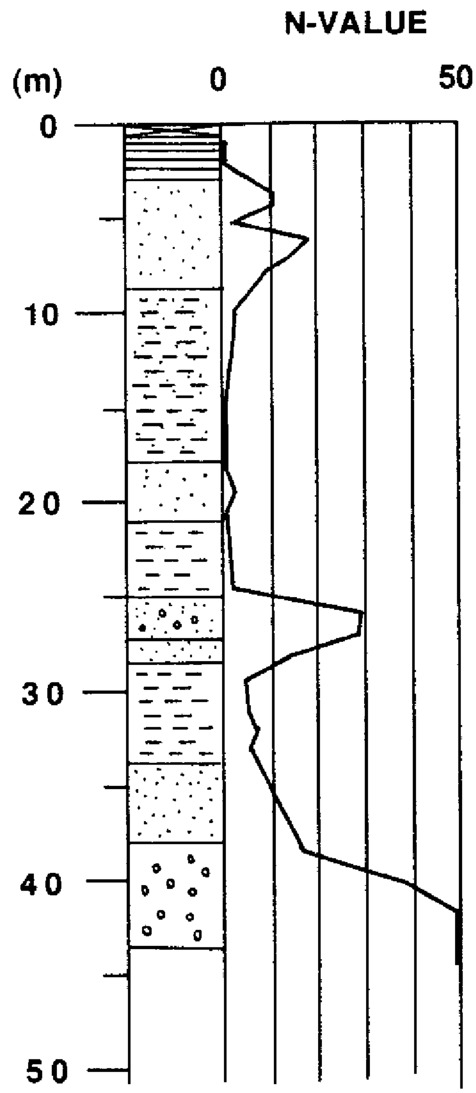

Fig.9-4 Soil Profile for the Shimonaga Site (Kubota Corp. Soil Strain Installation)

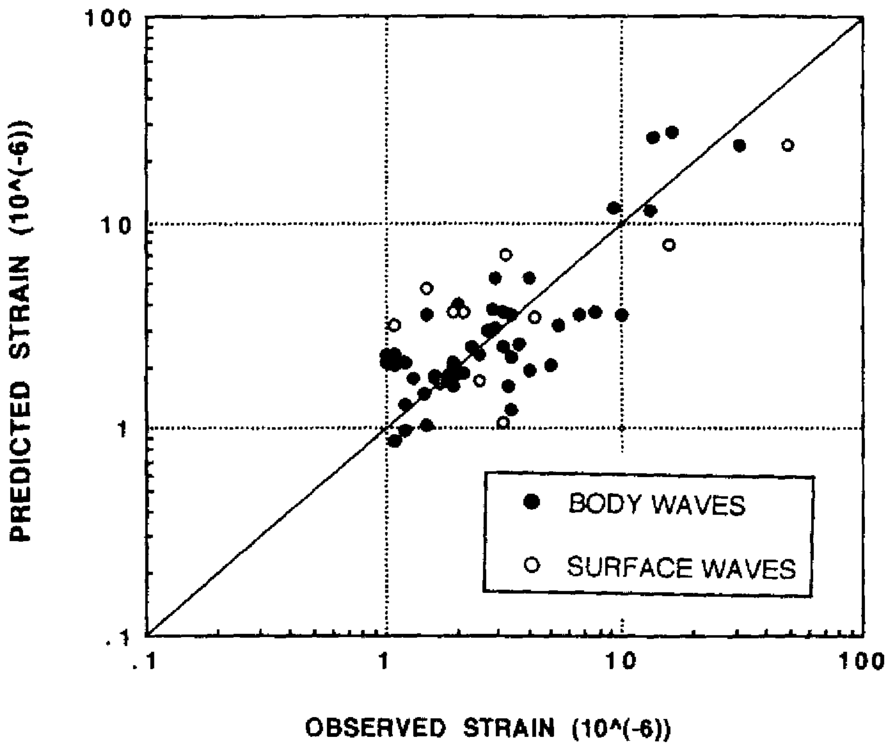

Fig.9-5 Comparison Between Observed Soil Strain at the Kubota Corp. Kansen Site and Predicted Values from Eqs.(9.3) or (9.4)

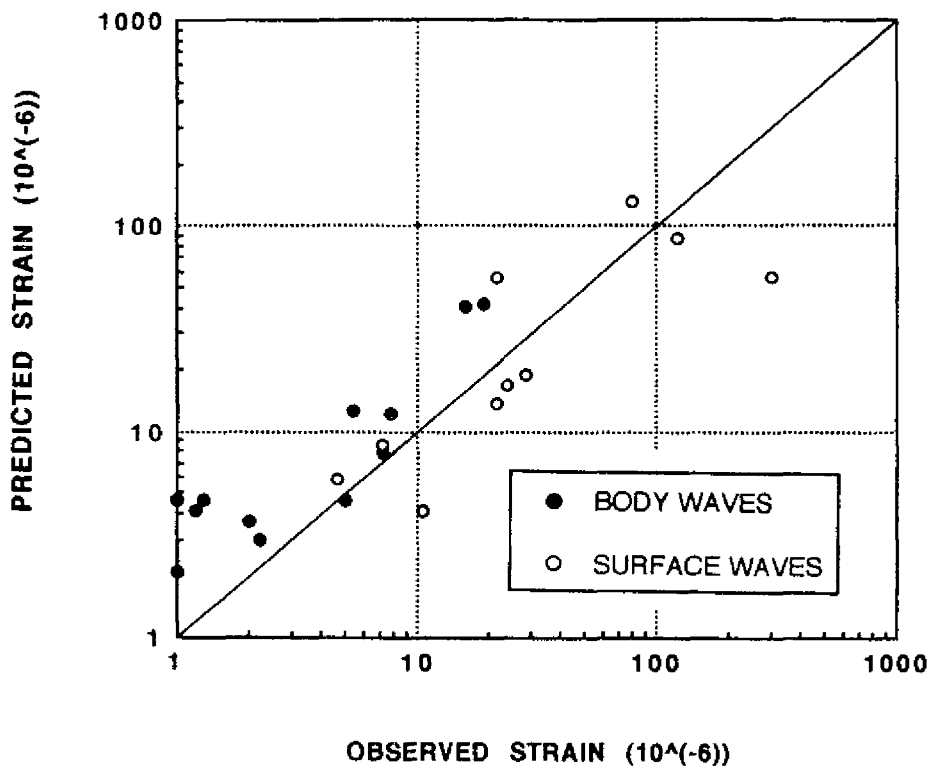

Fig.9-6 Comparison Between Observed Soil Strain at the Kubota Corp. Shimonaga Site and Predicted Values from Eqs.(9.3) or (9.4)

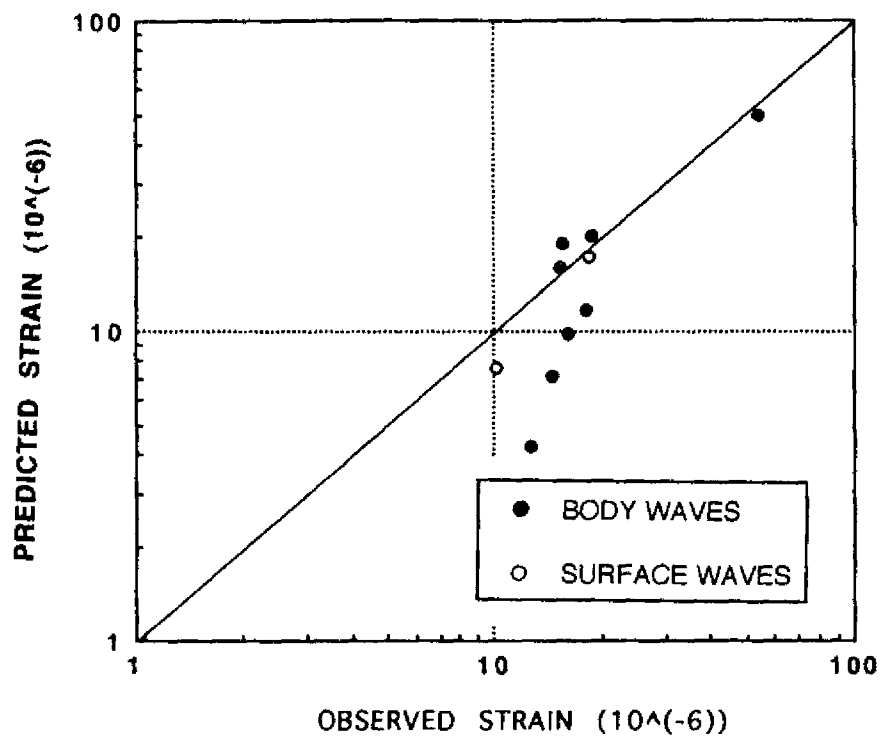

Fig.9-7 Comparison Between Observed Soil Strain at the Univ. of Tokyo Chiba Site and Predicted Values from Eqs.(9.3) or (9.4)

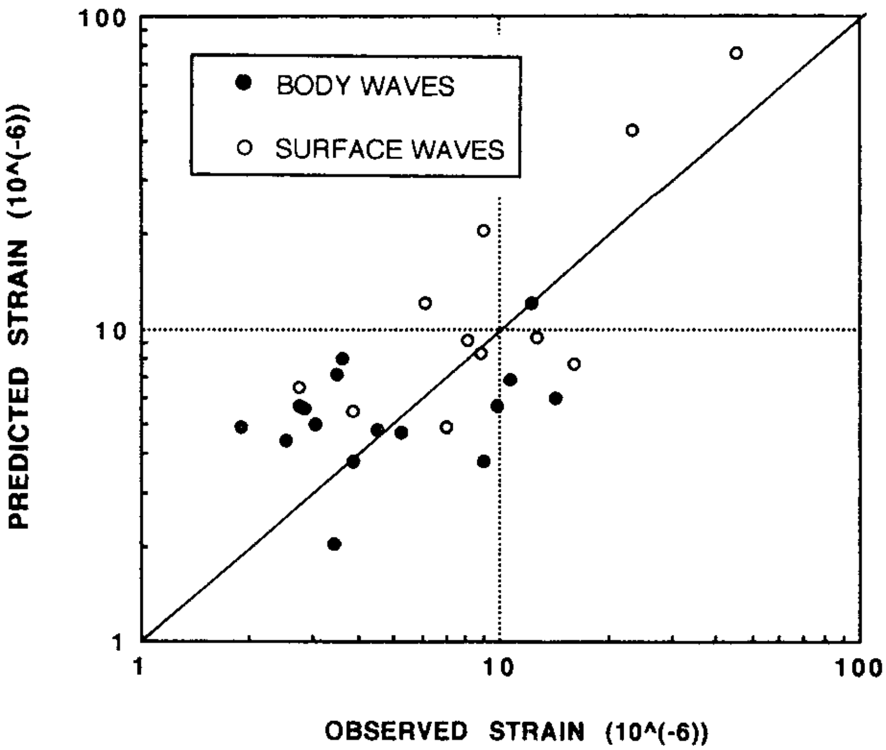

Fig.9-8 Comparison Between Observed Soil Strain at the Chubu Electric Power Corp.Chubu Site and Predicted Values from Eqs.(9.3) or (9.4)

and predicted values. Some of this scatter is attributed to errors in estimated values for the peak particle velocity, $\mathbf{v_{max}}$, as shown for example in Fig.4-3. Another source for error is inaccuracy in the measured soil strain. For example the measured strain would be less than the maximum soil strain at a site if the measuring device was not parallel to the direction of wave propagation. This is a possible explanation for points above the 1 to 1 match line in Figs.9-5 through 9-8. Finally for sites where surface waves are likely, we assume that the peak velocity, $\mathbf{v_{max}}$, occurs during the later surface wave portion of the record. In addition we assume that predominant period of that peak motion corresponds to the natural frequency of soil layer in shear. It is of course possible that the peak velocity, $\mathbf{v_{max}}$, may occur during the body wave portion of the record. It is also possible that the predominant frequency of surface waves is somewhat higher than $\mathbf{0.25C_L/h}$ and R-wave phase velocity in Fig.9-1 would hence be less than $\mathbf{0.875C_H}$. However if both these happen together, the soil strain which is a quotient might remain relatively unchanged from that given by Eq.(9.3).

SECTION 10
SUMMARY AND CONCLUSIONS

This report dealt with a semi-empirical model for estimating the peak values of strong motions with emphasis on the peak velocity which is needed for lifeline earthquake engineering studies. In the derivation of the model, theoretical information about seismic sources was combined with a statistical analysis of strong-motion data from Japan. The concept of dummy variables was used to obtain amplification factors due to individual local site conditions in the statistical analysis. An attenuation law for the peak acceleration, peak velocity and peak displacement on a rock was also obtained in terms of earthquake magnitude and hypocentral distance. The resulting amplification factors for peak velocity due to local site conditions were examined in connection with spectral amplification and soil profile, providing a method to predict the amplification factor at a new site. In addition, the resulting attenuation law for peak values on a rock was successfully compared with strong-motion data observed during three representative earthquakes in the U.S. and Mexico. Attenuation laws for strong motions by other researchers were also compared against the proposed model. Finally, a simplified method for estimating soil strain was developed. The main conclusions from this study are summarized as follows:

(1) Purely empirical models for prediction of strong-motion parameters suffer due to the fact that there usually is a correlation between the supposed independent variables in the strong-motion data. It is possible to overcome this difficulty as done herein by employing a standard attenuation coefficient empirically derived from extensive earthquake data collected by JMA.

(2) Amplification factor due to local site effects depends on the individual observation sites in contrast to the rough classification system commonly used by other researches. We developed a method for obtaining amplification factors at each observation site with the help of dummy variables. Results indicated that amplification factors vary remarkably from site to site and also depend on motion characteristics of interest, i.e.: acceleration, velocity and displacement.

(3) From a comparison against the amplification spectra, it was concluded that acceleration amplification is exclusively determined by period components less than about 0.3 sec while velocity's amplification is closely related to period components greater than about 1.0 sec. These amplification factors are also intimately related to the soil profile. In this study, we proposed two methods for predicting amplification factors, the "qualitative method" and "quantitative method." In the former method the amplification factor is estimated by a visual comparison of soil profiles. In the latter method the amplification factor is calculated from the distribution of N-values in the soil profiles.

(4) Besides the amplification factors due to local site effects, we obtained a set of attenuation laws for peak values on the seismic bed rock using the proposed model The seismic bed rock was defined based on the selection of reference site for the regression analysis and then a reconsideration based upon the resulting amplification factors. For example, the seismic bed rock for peak velocity corresponds to the rock outcrop at OFUNATO whose shear wave velocity is about **2000** m/sec. The attenuation laws for seismic bed rock are expressed in terms of earthquake magnitude and hypocentral distance. The expressions for attenuation including the amplification factors $\mathbf{AMP_j}$ are given in Eqs.(5.1) to (5.6).

(5) On the assumption that earthquake strong motions are analogous to simple harmonic motion, we obtained a rough estimate of the predominant periods of acceleration and velocity motions expected at a rock site. The resultant predominant periods, which are summarized in Table 6-I, indicated a tendency of longer periods with increasing earthquake magnitude. Also the resulting predominant periods compared favorably with observations by Seed et al.

(6) The peaks of strong motions at a rock site predicted by the proposed model were compared with the observed values from the 1989 Loma Prieta earthquake, the 1985 Michoacan earthquake and 1971 San Fernando earthquake. It was shown that the proposed model predicts relatively well the observed data. In particular, we found a good agreement between the predicted and observed values in the comparisons of peak velocity which is a primary goal of this study. Since the proposed model was based solely on Japanese strong-motion data, this suggests that strong-motion peaks have a common attenuation law irrespective of country of origin. Empirical models developed by other researchers, though established using the strong-motion data in the U.S., were also compared with the proposed semi-empirical model. The comaprison showed that these existing empirical relarions do not provide better estimates to the observed data than the proposed semi-empirical model.

(7) Based upon the proposed semi-empirical model for peak velocity, a simplified method for estimating maximum normal or longitudinal soil strain was developed herein. A comparison of predicted strains with observed values showed that the simplified method is reasonably accurate.

Finally it is pointed out that the basic logic used in this report could be used to estimate not only peaks of strong motions but also other parameters related to earthquakes.

In this report, some simplified procedures were adopted based on practical considerations. For instance, the derivation of the amplification factors for a soil profile was performed using only typically available N-value data for soil, and deep layers down to real bed rock were not considered. Using more detailed soil and rock information, more accurate amplification factor could be obtained. Furthermore, non-linear material characteristics of soft soils were not dealt with in this report. These problems are open questions for possible further study.

SECTION 11
REFERENCES

1. Okamoto, S., Introduction to Earthquake Engineering, University of Tokyo Press, 1984, pp.65-96

2. Barenberg, M. E., Correlation of Pipeline Damage with Ground Motions, Journal of Geotechnical Engineering, Vol.114, No.6, 1988, pp.706-711

3. Aki, K., Seismological Synthesis of Strong Ground Motion, Proc. 9th World Conf. on Earthq. Eng., Vol.3, 1988, pp.9-17

4. Luco, J.E., On Strong Ground Motion Estimated Based on Models of the Radiated Spectrum, Bull. Seism. Soc. Am., Vol.75, No.3, 1985, pp.641-649

5. Joyner, W.B. and Boore, D. M., Measurement, Characterization and Prediction of Strong Ground Motion, in Earthquake Engineering and Soil Dynamics, Vol.2(Ed. J.L. Von Thun), ASCE, 1988, pp.103-155

6. Campbell, K.W., Strong Motion Attenuation Relations: Ten-Year Perspective, Earthquake Spectra, Vol.1, No.4, 1985, pp.759-804

7. Campbell, K.W., Near-Source Attenuation of Peak Horizontal Acceleration, Bull. Seism. Soc. Am., Vol.71, 1981, pp.2039-2070

8. Fukushima, Y. and Tanaka, T., A New Attenuation Relation for Peak Horizontal Acceleration of Strong Earthquake Ground Motion in Japan, Bull. Seism. Soc. Am., Vol.80, No.4, 1990, pp.757-783

9. Kamiyama, M. and Yanagisawa, E., A Statistical Model for Estimating Response Spectra of Strong Earthquake Ground Motions With Emphasis on Local Soil Conditions, Soils and Foundations, Vol.26, No.2, 1986, pp.16-32

10. Draper, N. R. and Smith, H., Applied Regression Analysis, New York, John Wiley And Sans Inc., 1966

11. Joyner, W.B. and Boore, D.M., Peak Horizontal Acceleration and Velocity from Strong-Motion Records Including Records from the 1979 Imperial Valley, California, Earthquake, Bull. Seism. Soc. Am., Vol.71, 1981, pp.2011-2038

12. Trifunac, M.D., Preliminary Analysis of the Peaks of Strong Earthquake Ground Motion - Dependence of Peaks on Earthquake Magnitude, Epicentral Distance, and Recording Site Conditions, Bull. Seism. Soc. Am., Vol.66, 1976, pp.189-219

13. Richter, C.F., Elementary Seismology, Freeman, San Francisco, 1958

14. Kanbayashi, Y. and Ichikawa, M., A Method for Determining Magnitude of Shallow Earthquakes Occurring in and around Japan, Quarter Journal Seismology, Vol.41, 1977, pp.57-61(in Japanese)

15. Aki, K., Asperities, Barriers, Characteristic Earthquakes and Strong Motion Prediction, Journal Geophys. Res., Vol.89, No.B7, 1984, pp.5867-5872

16. Papageorgiou A.S. and Aki, K., A Specific Barrier Model for the Quantitative Description of Inhomogeneous Faulting and the Prediction of Strong Ground Motion, Part 1 and Part 2, Bull. Seism. Soc. Am., Vol.73, 1983, pp.693-722, pp.953-978

17. Ida, Y. The Maximum Acceleration of Seismic Ground Motion, Bull. Seism. Soc. Am., Vol.63, 1973, pp.959-968

18. Chin B.H and Aki, K., Simultaneous Study of the source , Path, and Site Effects on Strong Ground Motion During the 1989 Loma Prieta Earthquake: A Preliminary Result on Pervasive Nonlinear Site Effects, Bull. Seism. Soc. Am., Vol.81, No.5, 1991, pp.1859-1884

19. Kamiyama, M. and Matsukawa, T., An Empirical Scaling of Strong-Motion Spectra with Application to Estimate of Source Spectra, Structural Eng. and Earthq. Eng.(Proc. of Japan Soc. Civil Eng.), Vol.7, No.2, 1990, pp.331-342

20. Tsuchida, H. et al., Annual Report on Strong-Motion Earthquake Records in Japan Ports 1968-199, Technical Notes of the Port and Harbor Research Institute, No.98-No.649, The Port and Harbor Research Institute, Ministry of Transport, 1969-1990

21. Iwasaki, T. et al., Strong-Motion Acceleration Records from Public Works in Japan No.1-No.8, Technical Notes of the Public Works Research Institute, Vol.32-38, The Public Works Research Institute, Ministry of Construction, 1978-1983

22. Iai, S., Kurata, E. and Tsuchida, H., Digitization and Correction of Strong-Motion Accelerograms, Technical Note of the Port and Harbor Research Institute, No.286, 1978, pp.5-56(in Japanese)

23. Sato, R., Theoretical Basis on Relationship Between Focal Parameters and Earthquake Magnitude, Journal Phys. Earth, Vol.27, 1979, pp.353-372

24. Tsuchida, H. et al., Site Characteristics of Strong-Motion Earthquake Stations in Ports and Harbors in Japan (Part 1, 2 and 3), Technical Note of the Port and Harbor Research Institute, No.34, 107, 156, 1967-1973

25. Seed, H.B., Idriss, I.M. and Kiefer, F.W., Characteristics of Rock Motions During Earthquakes, Journal of Soil Mechanics and Foundations, ASCE, 1969 Septm, pp.1199-1218

26. McGuire, R.K., Seismic Ground Motion Parameter Relations, Journal Geotech. Eng. Div., ASCE, Vol.104, 1978, pp.481-490

27. Joyner, W.B. and Boore, D.M., Prediction of Earthquake Response Spectra, U.S. Geological Survey, Open-File Report 82-977, 1982, pp. 1-16

28. Campbell, K.W., Predicting Strong Ground Motion in Utah, in Evaluation of Regional and Urban Earthquake Hazards and Risks in Utah, 1988

29. Sabetta, F. and Pugliese A., Attenuation of Peak Horizontal Acceleration and Velocity from Italian Strong-Motion Records, Bull. Seism. Soc. Am., Vol.77, 1987, pp.1491-1513

30. Ohsaki, Y., Sawada, Y., Hayashi, T. Omura, H. and Kumagai, C., Spectral Characteristics of Hard Rock Motions, Proc. 7th World Conf. on Earthq. Eng., Vol.1, 1980, pp.231-238

31. Watabe, M. and Tohodo, M., Research on the Design Earthquake Ground Motions, Transaction of Architechture Institute of Japan, No.303, 1981, pp.41-51(in Japanese)

32. Kawashima, K., Aizawa, K. and Takahashi, K., Attenuation of Peak Ground Motion and Absolute Acceleration Response Spectra, Proc. 8th World Conf. on Earthq. Eng., Vol.2, 1984, pp.257-264

33. Shakal, A. et al., CSMIP, Strong-Motion Records from the Santa Cruz Mountains(Loma Prieta), California Earthquake of 17 October 1989, Report OSMS 89-06, 1989

34. UNAM, Institute of Engineering(II), Catalogo de Acelerograms por Fechas, Internal Report, 1991

35. California Institute of Technology, Earthquake Engineering Research Laboratory, Strong Motion Earthquake Accelerograms, Corrected Accelerograms and Integrated Ground Velocities and Displacements, Vol.2, Parts A-Y, 1971-1975

36 Hirasawa, T. and Stauder W., On the Seismic Body Waves from a Finite Moving Source, Bull. Seism. Soc. Am., Vol.55, 1965, pp.237-262

37. O'Rourke, M.J., Bloom, M. and Dobry, R., Apparent Propagation Velocity of Body Waves, International Journal of Earthquake Engineering and Structural Dynamics, Vol.10, 1982, pp.283-294

38 O'Rourke, M.J., Castro, G. and Hossain, I., Horizontal Soil Strain due to Seismic Waves, Journal of Geotechnical Engineering, Vol.110, No.9, 1984, pp.1173-1187

39 Nakamura, S., Prediction of the Characteristics of Surface Wave Considering Irregularity of Stratum and Application to Design, Doctoral Thesis, Tohoku University, 1989

40. Iwamoto, T. Yamamura, Y. and Miyamoto, H., Observation on Behaviors of Buried Pipelines and Ground Strain During Earthquakes, Proc. 9th World Conf. on Earthq. Eng., Vol.7, 1988, pp.35-41

41. Sato, N., Katayama, T. Nakamura, M., Iwamoto, T. and Ohbo, N., Observation of Seismic Ground Motion and Buried Pipe strain in a Very Dense Seismometer Array, Proc. 9th world Conf. on Earthq. Eng., Vol.7, 1988, pp.29-34

42. Ieda, R., Tsuchiyama, S., Nakamura, S. Yoshida, N. and Tsujino, S., Effect of Earthquake Motion on the Dynamic Behavior of Underground Transmission Line, Proc. 3rd International Conference on Soil Dynamics and Earthquake Engineering, 1987, pp.295-309