The Dynamic Response of Volcanic Soils

T.J. LARKIN
B.E., Ph.D., A.M.A.S.C.E.
Senior Lecturer, Department of Civil Engineering, University of Auckland
S.Y. CHAN
M.E.
Site Engineer, Binney and Partners Ltd, London, England

1. INTRODUCTION

This paper concerns the measurement of dynamic properties of some volcanic soils found in The New Zealand central volcanic plateau. Large areas of the central North Island are covered with this material or material of a similar type. The dynamic properties of this soil are important in predicting the response of this material to earthquake loading. There is a paucity of data on the dynamic properties of volcanic soils in New Zealand. This creates uncertainties in the use of analytical methods to calculate seismically induced ground motion.

Many of the analyses performed in New Zealand use overseas data to estimate the dynamic properties. The results of site response analyses are particularly sensitive to the shear modulus - strain relationship as was shown by Larkin and Donovan (1). Thus it is of some importance that for reliable results of theoretical analyses dynamic properties actually measured from volcanic soils are used as the basis for constitutive models used in site response analyses. Many analyses predict amplification of the bedrock motion, sometimes by a large amount, thus the depth and properties of the near surface soils are of considerable importance in this area of work.

A study of the dynamic properties of two volcanic soils was undertaken using the dynamic torsion test equipment at the University of Auckland. Details of these two soils are given in Tables 1 and 2.

Table II Properties of Volcanic Soils.

	Atterberg Limits			Particle size (%)		
Sample name	PL	LL	PI	Clay Fraction	Silt Fraction	Sand Fraction
Rotorua	44	62	18	8	25	66
Rerewhakaaitu	33	51	18	18	57	25

The soils tested were obtained from a construction site in the Whakarewarewa State Forest Park from depths of 3m to 4m. The samples have been categorised into two types, known as Rotorua and Rerewhakaitu ash. The Table above shows the soils have low plasticity index (18%) and are classified as MH in the plasticity chart of Casagrande. The Rotorua ash samples contain coarser particles than the Rerewhakaaitu ash and from visual observation the Rotorua ash is described as sandy silt while the Rerewhakaaitu ash is clayey silt.

The principle objective of the testing programme was to obtain dynamic properties of saturated ash soils as a function of shear strain at various effective confining pressures. This data may then be compared with the overseas data base used as a basis for the dynamic properties of soils in earthquake analyses. The laboratory confining pressures ranged from 25kPa to 150kPa.

Table I Properties of Volcanic Soils.

SAMPLE NAME	SAMPLE DESCRIPTION	WATER CONTENT (%)		BULK DENSITY (kg/m³)		VOID RATIO		Sr (%)		SOLID DENSITY (kg/m³)
		Before	After	Before	After	Before	After	Before	After	
Rerewhakaaitu 1	grey brown clayey silt	61.7	55.6	1479.2	1516.7	1.7	1.5	90	90	2466.1
Rerewhakaaitu 2	grey brown clayey silt	54.9	64.0	1533.0	1563.2	1.5	1.6	91	99	
Rotorua 1	yellow brown sandy silt with soft pumice pebbles and organic roots.	51.6	66.3	1429.1	1545.5	1.6	1.6	80	100	2412.8
Rotorua 2	yellow brown sandy silt with soft pumice pebbles and organic roots	50.2	62.2	1355.6	1487.3	1.7	1.6	73	92	
Rotorua 3	yellow brown sandy silt with soft pumice pebbles and organic roots.	44.6	65.1	1313.7	1552.3	1.7	1.6	65	100	

A detailed description of the free vibration torsion test equipment and the testing and analysis technique is contained in Chan(2). This work describes the enhanced system of date collection and analysis and the experimental results presented here.

2. DYNAMIC TEST RESULTS

A series of free vibration torsion tests were performed on the volcanic ash soils whose properties are shown in Tables 1 and 2. The unprocessed data takes the form of torsional displacement of the sample as a function of time. This data was then processed to compute shear modulus and damping curves. Examples of the results of this process are shown in Figure 1 and Figure 2. These results show the strongly nonlinear nature of the soil response with the shear modulus decreasing with increasing shear strain after a constant modulus response (low strain plateau) in the very low strain range. The equivalent viscous damping factor increases with increasing strain to peak values of approximately 20%. These general trends are in line with the international body of literature on the results of dynamic tests on soils, although some features of these results on volcanic soils differ from overseas data, as will be discussed later.

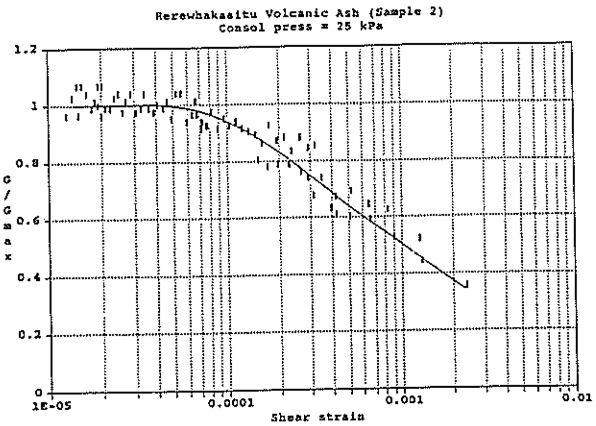

Figure 1. Typical variation of shear modulus with shear strain.

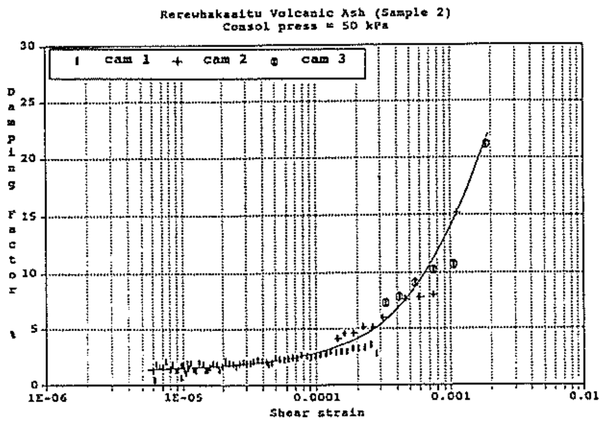

Figure 2. Typical variation of damping factor with shear strain.

A series of tests at different confining pressures were carried out on the two volcanic soils. The results of these tests are summarised in Table 3 where values of the low strain shear modulus, G_{max}, and damping factor, D_{min}, are shown for five different cell pressures, along with the low strain shear wave velocity.

These results show that the low strain shear modulus and damping ratio are stress dependent and hence in any soil profile are a function of the depth, with higher confining stress resulting in higher shear moduli and lower damping. This variation in dynamic properties with confining stress is shown in Figure 3 and Figure 4. The value of shear modulus is sensitive to the stress level while the damping factor is very insensitive for the soils tested. Within the stress range tested the shear modulus is approximately a linear function of the confining stress.

2.1 Comparison of test results with other investigators.

The purpose of summarising data on shear modulus and damping curves is to provide useful guidelines on the form of the relationship for typical soils. This information can be used for preliminary investigations or when no other data will be available. In this study the volcanic ash test results are compared with recent papers of summarised data for clays and sands. Sun et al (3) concentrated on clays while Seed et al (4) collected various data for sands and gravelly soils.

2.1.1 Shear modulus curves.

A summary of the shear modulus curves of the two volcanic soils tested is shown in Figure 5. Generally speaking the following features may be identified:

(1) Rotorua curves (bold lines) are flatter than Rerewhakaaitu. This is expected since Rotorua samples are more sandy, and is consistent with the general trend that curves for sands are flatter than for clays.

(2) For both Rotorua and Rerewhakaaitu samples, the G/G_{max} curves essentially move to the left, as the confining pressure increase. However, the change

Table III Variation of Properties with Confining Stress.

	Rerewhakaaitu			Rotorua		
Confining pressure (kPa)	G (MPa)	V_s (m/s)	D_{min} (%)	G (MPa)	V_s (m/s)	D_{min} (%)
25	11.3	84.9	1.7	-	-	-
50	15.0	98.0	1.7	23.7	123.8	1.3
75	19.0	111.9	1.5	-	-	-
100	23.4	124.3	1.3	40	164	-
150	34.0	149.8	1.0	42.8	166.0	1.3

is not very significant. This is consistent with other reports for clays and sands. Sun et al (3) state that the influence of confining pressure is generally small for clays with plasticity indices exceeding 25 and for shear strains less than 0.01. For sands, studies by Hardin & Drnevich (5), Shibata & Soelarno (6) and Iwasaki et al (7) show that G/G_{max} curves are slightly influenced by the confining pressure.

2.1.2 Damping curves

Figure 6 summarizes the damping curves for the Rotorua and Rerewhakaaitu samples. The damping curves are essentially independent of the confining pressure, which is consistent with various reports for clays and sands. Sun et al (3) reports that damping curves for clays have not significantly deviated from the range indicated by Seed & Idriss (8), implying that confining pressure has a limited influence on damping characteristics of clays. For sands, Seed et al (4) state that at pressures greater than 500 psf (24 kPa), the effect of confining pressure is small compared with the effect of shear strain.

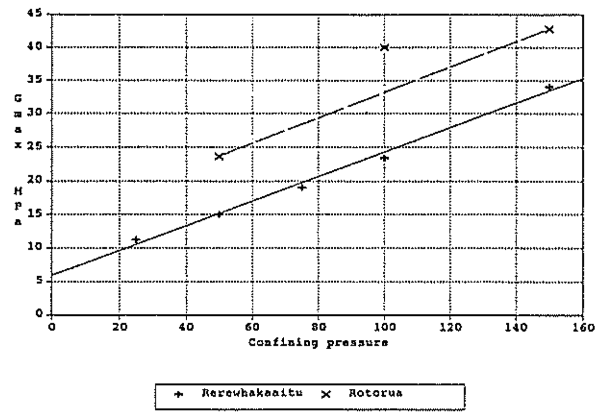

Figure 3. G_{max} variation with effective confining pressure.

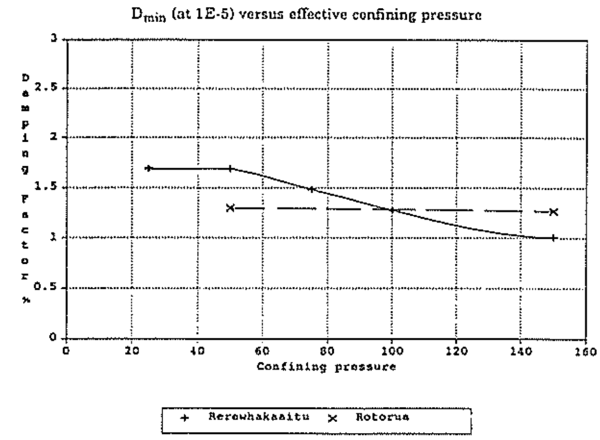

Figure 4. D_{min} versus effective confining pressure.

2.2 Volcanic ash Compared with clays.

2.2.1 Normalized shear modulus curves.

Sun et al (3) conclude that normalized shear modulus curves for clays are most significantly influenced by the plasticity index (PI). Figure 7, after Zen and Higuchi,(9) provides a useful guide on the form of normalized shear modulus curves with respect to shear strain and PI. In addition, void ratio may be a significant secondary factor to be considered in selecting a normalized shear modulus curve for analysis purposes. In this study, the void ratios are essentially unchanged with confining pressure and hence its effect is insignificant.

Figure 7 compares G/G_{max} curves between volcanic ash samples and clays Zen and Higuchi, (9). Because the volcanic ash samples have a PI of 18, it is expected that their curves lie near the PI boundary of 20. Between strains of $7*10^{-5}$ and $2*10^{-3}$ the volcanic ash curves essentially lie near the PI=20 boundary, and hence close

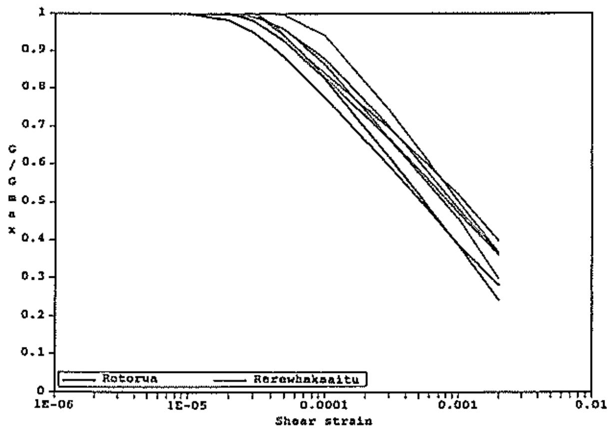

Figure 5. Normalised shear modulus curves for Volcanic Soils.

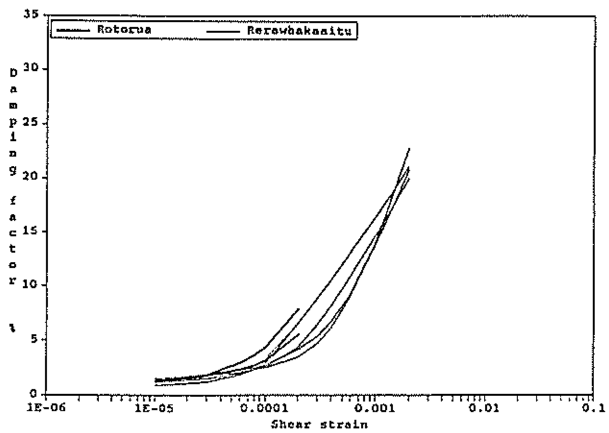

Figure 6. Damping curves for volcanic soils.

comparison is evident. At smaller strains ($<7*10^{-5}$), two differences are observed.

(1) The volcanic ash curves have a more extended G/G_{max} plateau ($G/G_{max}= 1$). This 'elastic' behaviour is maintained to strains of 1 to $5*10^{-5}$.

(2) The volcanic ash curves rapidly drop away from the plateau, starting between strains of $1*10^{-5}$ and $1*10^{-4}$. This is in contrast with the more gradual decay of the PI boundaries.

In summary, although the volcanic ash G/G_{max} curves are consistent with the proposed curves of Zen and Higuchi (9) for a wide range of strain, there is a potential for volcanic ash curves to deviate from Zen and Higuchi's curves at smaller strains.

2.2.2 Damping curves

Reported values for the damping curves of clays have not significantly changed from the boundaries indicated by Seed and Idriss in 1970. Figure 8 depicts the comparison between volcanic ash curves and Seed & Idriss (8). There are three observations.

(1) At low strains (<0.0001) volcanic ash curves have low damping values and are positioned at the lower boundary of Seed & Idriss (8).

(2) At higher strains (>0.0001), volcanic ash curves show a steep gradient and hence, the curves travel from the lower boundary at low strains to the higher boundary at higher strains.

(3) The volcanic ash curves essentially lie within the boundaries of Seed & Idriss (8). Judging from the gradient of the volcanic ash curves, it appears that the damping can be significantly higher than Seed & Idriss at high strains (>0.002) but this is still to be experimentally verified.

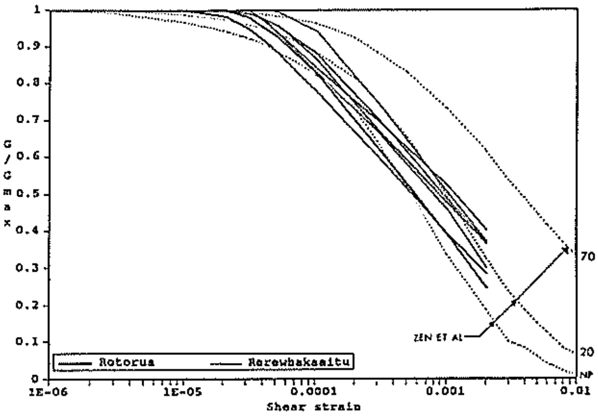

Figure 7. Comparison of G/G_{max} for volcanic ash and clays.

2.3 Volcanic ash compared with sands and gravelly soils.

2.3.1 Normalized shear modulus curves.

Seed et al (4) report that the boundaries indicated by Seed & Idriss (8) are generally representative of most sands. The curve for gravels may be a little flatter than that for sands.

Figure 9 compares volcanic ash curves and boundaries of Seed & Idriss (8). The following are observed:

(1) The volcanic ash curves have more extended G/G_{max} plateaus.

(2) Similar to the comparison with clays, the volcanic ash curves exhibit a sudden and rapid decay (between $1*10^{-5}$ and $1*10^{-4}$) as opposed to the more gradual decay of the boundaries for sands.

(3) The volcanic ash curves are not located near the mean curve for sands. Instead, they generally lie near the upper boundary. Hence, the volcanic ash curves do not closely compare with the mean curve of Seed & Idriss (8).

2.3.2 Damping curves.

Seed at al (4) concludes that damping ratios for sands and gravels are very similar. Figure 10 compares volcanic ash damping curves and the boundaries suggested by Seed et al (4). The observations are similar to those noted for volcanic ash versus clays. It is interesting to note that at low strains (<0.0001), volcanic ash curves consistently lie near the lower boundary for both sands and clays.

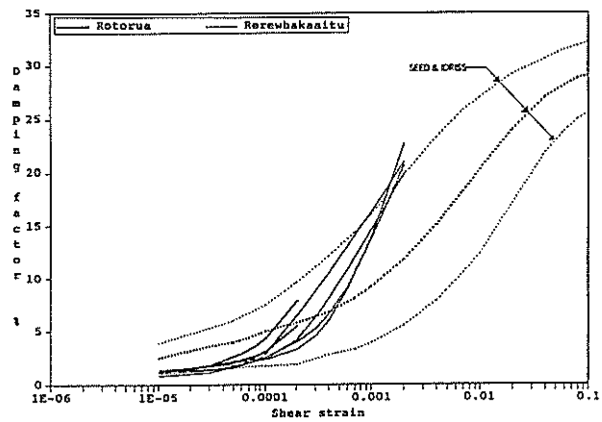

Figure 8. Comparison of damping curves for volcanic ash and clays.

2.4 Comparison of volcanic ash and residual Waitematas.

This comparison is initiated in an attempt to see if volcanic ash curves are significantly different from some known curves of local soils, obtained using the same equipment. Parton(10) and Larkin and Taylor(11) obtained curves for saturated residual Waitematas while

Plested(12) obtained results related to unsaturated residual Waitematas. It was found that the volcanic soils responded similarly to unsaturated Waitematas as far as shear modulus was concerned while the damping factors showed little correlation.

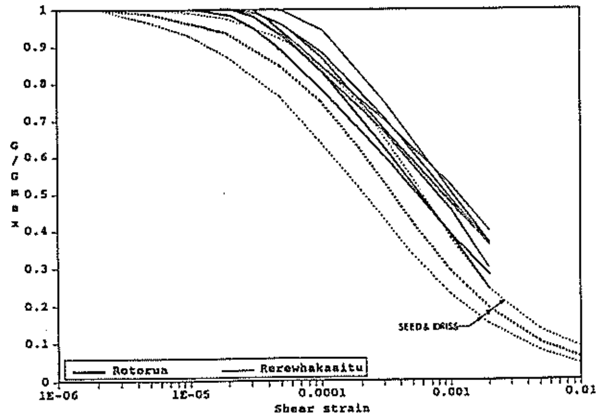

Figure 9. Comparison of G/G_{max} for volcanic ash and sands.

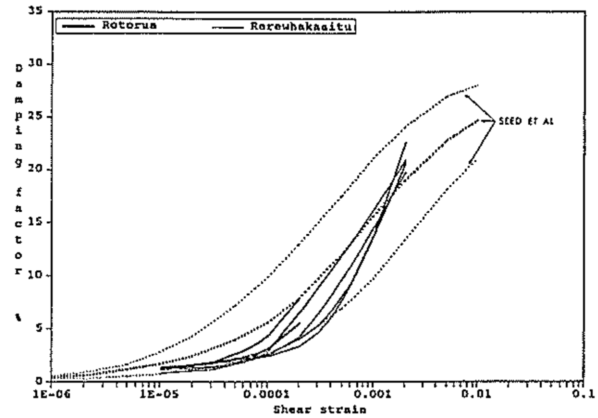

Figure 10. Comparison of damping curves for volcanic ash and sands.

3. SENSITIVITY OF SOIL RESPONSE ANALYSES TO DYNAMIC SOIL PROPERTIES.

The evaluation of dynamic soil properties is one of the key parameters used in theoretical seismic site response studies. This section of work investigates the sensitivity of computed results to variation in dynamic soil properties, especially with respect to volcanic soils. A comparison is made between the calculated earthquake response of a 30 metre layer of volcanic soil using the internationally used data base for sands and nonplastic silts, Seed and Idriss(8) and the data base formed from the measured properties presented in this paper.

The overseas data base for sands is shown in Figure 9 and in the absence of other information may be the source of the dynamic properties used in an analysis. This data base uses a value of G_{max} that is proportional to the square root of depth, where as the experimental data shows essentially a linear variation in G_{max} with depth, see Figure 3. Thus the maximum shear wave velocity at the

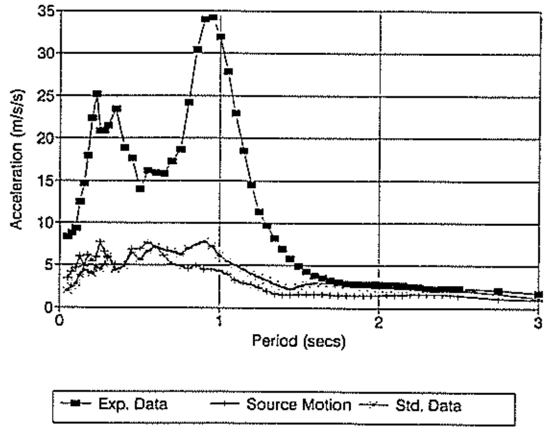

Figure 11. Comparison of Surface Response Spectra.

soil/bedrock interface predicted for the volcanic soil on the basis of the experimental work presented here is 146 m/s, while that obtained using the data set of Seed and Idriss is 262 m/s. This significant factor along with a different relationship between shear modulus and shear strain form the differences in the analyses. The overseas data base was used with an estimation of the relative density of the soil of 70%.

The 30m profile was analysed using a method of nonlinear analyses described by Larkin (13) using the computer program DENSOR. The earthquake used had a peak bedrock acceleration of 0.3g. Figure 11 shows the ground surface response spectra computed using the two data bases as input for the constitutive relationship for the soil. The figure shows the very marked difference in the spectra obtained from the two analyses. The surface response using the experimental data from this study is up to four times that using the existing standard data base established for sands. Very different conclusions and design constraints would result from the analyses. This example illustrates the sensitivity of dynamic analyses to the soil property data and highlights the need for much care and investigation of alternatives when performing theoretical seismic soil response analyses. The divergence of results is caused mostly by the difference in the way G_{max} varies as a function of the overburden stress, but the results are also sensitive to the shape of shear modulus curve.

4. CONCLUSIONS

Normalized shear modulus and damping curves for the volcanic ash samples did not significantly deviate from the general trend of proposed 'standard' curves for clays and sands. It is concluded that the volcanic ash modulus curves fit well with the 'standard' curves for clays while the damping curves fit slightly better with sands. When compared with some limited data of local Waitemata soils, the volcanic ash modulus curves showed similar behaviour to unsaturated Waitematas while the damping curves did not indicate any observable trend.

The above comparisons have also revealed certain characteristics of the volcanic ash curves which are different to the 'standard' curves of clays and sands.

The following conclusions are for the volcanic ash samples

(1) The G/G_{max} and damping curves are essentially independent of confining pressure.

(2) Volcanic ash G/G_{max} curves fit reasonably well with summarized G/G_{max} curves for clays. In contrast, they do not fit well with sands because they are much higher than the mean curve.

(3) Volcanic ash damping curves fit slightly better with sands than clays in the sense that the curves are relatively closer to the mean curve for sands for most parts of the strain range.

(4) The volcanic ash G/G_{max} curves show similar behaviour with unsaturated Waitematas. Saturated Waitematas, on the other hand, are located to the right, indicating a more gradual attenuation. No trend was observed for the damping curves. Further data is needed to confirm these results.

(5) The volcanic ash G/G_{max} curves contain longer low strain plateaus, reaching $5*10^{-5}$. In addition, the attenuation from the plateau are sudden and rapid - this occurs between strains of $1*10^{-5}$ and $1*10^{-4}$.

(6) The volcanic ash damping curves indicate low damping factors at low strains ($<1*10^{-1}$), steep curve gradients at higher strains ($>1*10^{-4}$) and damping values which are possibly significantly higher than the mean curves of clays and sands for strains greater than 0.002.

The results of a seismic analysis of a layer of volcanic ash soil is shown to be very sensitive to the dynamic soil properties used. Care must be taken in selecting such properties and a number of analyses performed to gauge the spread of results and the sensitivity to the data.

REFERENCES

1. LARKIN,T.J. and DONOVAN N.C.(1979). "Sensitivity of Computed Nonlinear Effective Stress Soil Response to Shear Modulus Relationships", Proc Second US National Conference on Earthquake Engineering, Stanford, August, pp. 573-582.

2. CHAN, S.Y. (1990) Measurement of Dynamic Properties of Some Volcanic Ash Soils., M.E.Thesis Department of Civil Engineering, University of Auckland.

3. SUN et al (1988) Dynamic Moduli and Damping Ratios for Cohesive Soils, Report No. UCB/EERC-88/15. University of California, Berkeley, August.

4. SEED et al (1986) "Moduli and Damping Factors for Dynamic Analyses of Cohesionless Soils". J.Geotechnical Eng., ASCE, Vol.112, No.11, pp. 1016-1032.

5. HARDIN, B.O. and DRNEVICH, V.P. (1972). "Shear Modulus and Damping in Soils : Design Equations and Curves." J.Soil Mechs and Found Div, ASCE, 98(7), pp. 667-692.

6. SHIBATA,T and SOELARNO, D.S. (1975). "Stress-strain Characteristics of Sands Under Cyclic Loading". Proc Japanese Society of Civil Engineers, No.239.

7. IWASAKI, T, et al (1976). "Dynamic Shear Deformation Properties of Sands for Wide Strain Range." Report of Civil Engineering Institute, No.1085, Ministry of Construction, Tokyo, Japan.

8. SEED, H.B. and IDRIS, I.M. (1970). Soil Moduli and Damping Factors for Dynamic Response Analysis, Report No. UCB/EERC-70/10, University of California, Berkeley.

9. ZEN,K and HIGUCHI, Y (1984). "Prediction of Vibratory Shear Modulus and Damping Ratio for Cohesive Soils". Proc Eighth International Conf on Earthquake Engineering, San Francisco, July, Vol.3, pp.23-30.

10. PARTON,I.M. (1972). Site Response to Earthquakes with reference to the Application of Microtremor Measurements, PhD thesis, University of Auckland.

11. LARKIN, T.J. and TAYLOR, P.W. (1977). Comparison of Downhole and Laboratory S Wave Velocities, Canadian Geotechnical Journal, Vol.16, pp. 152-162.

12. PLESTED, M.L. (1985). In situ Investigation of Shear Waves in Soil Media, PhD thesis, University of Auckland, School of Engineering Report No. 378.

13. LARKIN, T.J. (1979). "DENSOR - A Computer Program for Seismic Response Analysis of Nonlinear Horizontal Soil Layers", Report No. 51508-6, Norwegian Geotechnical Institute, Oslo, Norway.