Dynamic behaviour of fly ash under seismic conditions of Eastern Canada

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ABSTRACT

The dynamic behaviour of a fly ash was studied with particular reference to seismic ground motions that prevail in eastern Canada. Resonant column tests, cyclic simple shear tests and cyclic triaxial tests at both low and high frequencies have been conducted. The resonant column test measures the initial shear modulus and damping ratio of the fly ash. The cyclic simple shear test shears the fly ash in a horizontal direction that is realistic with the transmission of seismic shear wave in the field. The cyclic triaxial test at high frequency (10Hz) is consistent with the high frequency content of the seismic vibrations observed in this region. The test results have been analyzed to study the deformational characteristics and liquefaction resistance of the fly ash. The practical implications from the study are also discussed.

INTRODUCTION

Large amount of fly ash is produced annually in Canada as a result of burning coal for power generation. Some are stockpiled in open yards while others are stored in ponds or hauled to fill pits from which the coal was mined. Some are utilized commercially in various ways to produce economical and environmental benefits. One way is to turn fly ash into structural fill material (Toth et al. 1988). When such fills and stockpiles of fly ash are located in earthquake zones, the potential of liquefaction and other problems associated with dynamic loading are of public concern.

During an earthquake, horizontal shear stresses are transmitted from the bedrock to the overlying soil strata. A good laboratory method for measuring soil behaviour under seismic conditions therefore should involve testing soil specimen under a horizontal shearing mode. In eastern Canada, seismic ground motions are found to contain a significant high frequency content in the range of 10

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to 15 Hz (Adams 1989, personal communication). Dynamic soil behaviour in this frequency range is little known because of the lack of equipment to test soil in this range.

This paper describes a laboratory study on the dynamic behaviour of fly ash. A resonant column test device was used to measure the initial shear modulus and damping ratio of the material. A cyclic simple shear apparatus was used to shear soil specimens in a horizontal direction. A unique cyclic triaxial equipment has been used to measure cyclic strength at a high frequency.

The test results show that the fly ash is stronger at the high frequency range than at the usual test frequency of 1 Hz and that it is weaker in the cyclic simple shear mode than in the triaxial mode. The practical implications from the results are also discussed.

TEST PROGRAM

A sample of fly ash was obtained from the ash lagoon at the Ontario Hydro Nanticoke power generating station. The ash has a specific gravity in the range of 2.20 to 2.26. It was oven dried for more than 24 hours before being passed through the #200 sieve. The resulting ash has a mean grain size of 0.012mm and a coefficient of uniformity of 13.7. The ash was then mixed with 25% of water to form specimens for the test program.

The cyclic triaxial equipment used herein is one its kind in the western world. It uses an electro-magnetic drive to provide cyclic loads sufficiently large to fail test specimens at frequencies as high as 20 Hz. The details of this equipment are described by Law et al (1991). Undrained cyclic test isotropically consolidated to 50 kPa at 1 Hz and 10 Hz have been carried out.

The Seiken cyclic simple shear device has been used to impose horizontal shear to fly ash specimens. Compared with other devices, this device has a number of unusual features. Firstly, it permits the application of both the cell pressure and the back pressure to ensure specimen saturation during the test. Secondly, it does not require a steel wire reinforced membrane to provide a zero horizontal strain to maintain the simple shear condition. Ordinary rubber membrane is acceptable. Thirdly, the cell pressure can be varied at will so that any consolidation stress system, either isotropic or anisotropic, can be applied. For the present test series, undrained cyclic tests isotropically consolidated to pressures of 50 kPa and 150 kPa, have been conducted.

The Stokoe resonant column test cell has been used to apply torsional vibrations to a cylindrical specimen configured to a fixed-free type column. The bottom end of the specimen is rigidly fixed to the base while the top end is connected to a drive system for applying the torsional vibrations. The initial shear modulus was determined from the measured shear wave velocity in the specimen at a strain amplitude around 0.001%. The damping ratio was obtained by means of the logarithmic decrement method.

Specimens used in all the different tests were reconstituted using the moist tamping procedure. The specimens for the cyclic triaxial tests and the resonant column tests were 3.91 cm in diameter and 8 cm high and were formed in 8 layers. The specimens for cyclic simple shear tests were 7 cm in diameter and 1.8 cm high and were formed in one layer. The specimens were saturated first by passing carbon dioxide through the specimen under a small confining pressure to displace the air in the void space. This was followed by passing distilled water to replace the carbon dioxide. Any trace of carbon dioxide that remained in the sample dissolved in the pore water when a back pressure of 200 kPa was applied. This saturation procedure produced a pore pressure parameter of $\overline{B}$ of 0.96 or higher.

During the undrained cyclic triaxial and simple shear tests, readings were taken with an IBM PC AT compatible data acquisition system equipped with an integrated circuit board which provided up to 8 analogue to digital channels for taking readings. The computer is programmed to take 100 readings per second per channel for 1 Hz vibrations and one thousand readings per second per channel for 10 Hz vibrations. For a cycle in the cyclic triaxial test, therefore, 100 readings were taken of each of the excess pore pressure, vertical cyclic load and vertical displacement. Similarly, in the cyclic shear test, 100 readings were taken of each of the excess pore pressure, horizontal cyclic load, horizontal displacement and vertical load. After the test, the data were processed and the results were displayed on the monitor and on the plotter. For the resonant column tests, a high speed strip chart recorder was used to trace the torque.

TEST RESULTS AND ANALYSIS

Deformational characteristics

A summary of the results of the resonant column tests is shown in Table 1. Within the strain amplitude tested, the average damping ratio is 1.3% and the modulus value drops slowly with strain amplitude for a given consolidation pressure. The modulus value at around 0.001% was taken as the initial modulus (G_0) to analyze the cyclic test data in the following.

Table 1. Summary of results from resonant column tests

Consolidation Pressure kPa	Peak Shear Strain %	Modulus MPa	Damping Ratio%
50	0.0014	20.56	1.36
	0.0038	20.16	1.24
	0.0065	19.96	1.90
	0.0123	19.37	1.94
150	0.0010	37.40	1.20
	0.0026	37.40	0.67
	0.0057	37.12	0.91
	0.0085	36.57	1.14
	0.0110	36.30	1.17

A hyperbolic strain model (Hardin and Drnevich, 1972) is used to analyze the modulus degradation with strain amplitude. From the cyclic loading and resonant column tests, the functional relationship can be written as:

$$G = 1/(a+b*\gamma) \qquad (1)$$

where:

G = shear modulus
γ = shear strain
a,b = constants to be determined from the test results.

The values of "a" and "b" can be obtained by plotting 1/G vs γ as shown in Fig.1 for the cyclic simple shear tests at a consolidation pressure of 50 kPa. A straight line can be used to approximate the relationship with the intercept on the 1/G axis equal to "a" and the slope of the line equal to "b". By definition, the initial shear modulus, G_0, is the modulus value at zero shear strain. The value of "a" should therefore equal to $1/G_0$. This is the case in the present study as "a" from the cyclic simple shear tests agrees with $1/G_0$ from the resonant column tests.

Rewriting Eq.1, one obtains

$$G/G_0 = 1/(1+\gamma_1) \qquad (2)$$

where:

$\gamma_1 = \gamma/\gamma_r$ (normalized shear strain)
$\gamma_r = a/b$ (reference strain).

Fig.2 presents the test data, on the basis of the hyperbolic strain model, from the resonant column tests, cyclic simple shear tests and cyclic triaxial tests. The same G_0 and γ_r have been used in all these test data. The result shows that the cyclic simple shear test and resonant column tests give more or less the same modulus degradation curve. The cyclic triaxial tests however yield a higher modulus than the cyclic simple shear tests at comparable shear strain amplitudes.

Liquefaction resistance

The liquefaction resistance (τ_l) of a granular soil is defined as the uniform cyclic shear stress applied to the soil until failure occurs. Failure corresponds to the condition when the excess pore pressure reaches the initial consolidation pressure (σ_c'). The liquefaction resistance normalized by σ_c' for a given soil is a function of shearing mode, void ratio, frequency of loading and number of cycles or energy dissipated to the point of failure. Fig.3 shows typical test results from a cyclic simple shear test for σ_c'= 50 kPa.

Fig.4 shows the test results for σ_c'= 50 kPa for different shear modes, frequencies, void ratios and numbers of cycles to failure. The results show that the liquefaction resistance increases with increase in frequency and decrease in void ratio and number of cycles to failure. As well, the cyclic triaxial test yields a higher strength than the cyclic simple shear test for the same void ratio. For example, at 10 cycles to failure and at the loose state of void ratio of 1.285, the cyclic triaxial strength at 1 Hz is 12% higher than the cyclic simple shear strength at the same frequency and the cyclic triaxial strength is 11% higher at 10 Hz than at 1 Hz.

A number of researchers (He 1981, Davis and Berrill 1982 and Law et al. 1990) have proposed another approach of assessing liquefaction resistance based on the total energy dissipated in the soil during dynamic loading. The total dissipated energy (ΣW) consists of two components: one from plastic deformation and the other from hysteretic damping. The value of ΣW can be obtained by summing the areas covered by the plastic deformation and the hysteresis loops on a stress-strain plot for each test. The stress and the strain at any point of a test were evaluated from the data acquired by the high speed computer system.

Fig.5 shows some of the typical test results based on the energy approach. The vertical axis represents the excess pore pressure, Δu, normalized by the initial consolidation pressure, σ_c'. The horizontal axis represents the normalized total dissipated energy, W_N, defined by $\Sigma W/\sigma_c'$. The test shown in the figure corresponds to $\sigma_c' = 50$ kPa and void ratio = 1.285 and includes both the cyclic simple shear and cyclic triaxial shear. For a given shear mode, the results suggest that there exists a single relationship between $\Delta u/\sigma_c'$ and W_N, similar to that of a clean sand studied by Law et al. (1990). The relationship can be written as

$$\Delta u/\sigma_c' = \alpha W_N^{\beta} \qquad (3)$$

where α and β are constants to be obtained from the test results.

The results also show that for the same amount of dissipated energy, the triaxial test yields a lower excess pore pressure than the simple shear test. This is consistent with the earlier observation that soil sheared under the cyclic triaxial mode is stronger than under the cyclic simple shear mode.

Eq. 3 shows another aspect based on the energy approach. By definition at liquefaction failure, $\Delta u/\sigma_c'$ is equal to 1.0 and hence the normalized total dissipated energy at failure, W_{Nf}, is a constant. In other words, for a given shear mode, void ratio and consolidation pressure, liquefaction failure can be expressed by a single variable of W_{Nf}. In the conventional approach, however, two variables, the applied shear stress and the number of cycles of load application, have to be considered.

PRACTICAL IMPLICATIONS

The liquefaction resistance of the fly ash can be compared with that of similar soils reported in the literature. However it is recognized that the relative density of the materials being compared can not be ascertained as the grain size of the fly ash is too fine for determination of the maximum density based on the ASTM standard (D4253). The comparison presented here therefore can only be considered qualitative. By nature of formation, fly ash is similar to volcanic soil and by grain size distribution, it is similar to silt. Fig.6 compares the triaxial liquefaction resistance of the loose fly ash with a loose volcanic soil (Hatanaka et al. 1985) and a loose silt (Cao and Law 1991). The fly ash is stronger than the volcanic soil and silt. One possible reason for the relatively high strength is this fly ash has a friction angle of about 35°(Toth et al. 1988) even at a loose state.

The test results suggest that a conventional cyclic triaxial equipment that shears soil at a low frequency range around 1 Hz may yield reasonable liquefaction resistance for soils in eastern Canada provided that the field density can be maintained in the laboratory test. Here in this region, the seismic stress induced in the soil mass is horizontal and contains a high frequency content. The horizontal shear tends to lower the resistance while the high frequency loading tends to raise it. These two factors are compensating each other, hence giving support to the use of the conventional equipment which is far more commonly available than either the cyclic simple shear apparatus or the high frequency triaxial device.

The triaxial equipment, on the other hand, may overestimate the modulus as seen in Fig.4. This figure suggests that frequency has little effect on modulus as the same modulus degradation curve applies to both the resonant column test which was conducted at high frequency (about 25 Hz) and the cyclic simple test which was conducted at low frequency (1Hz). The modulus obtained from the triaxial will not be subject to a compensating effect similar to that for resistance.

SUMMARY AND CONCLUSIONS

A laboratory test study has been conducted on a fly ash from Nanticoke, Ontario. Tests have been performed by means of a cyclic simple shear apparatus in order to be more realistic compared with the shear mode in the field under earthquake condition. A unique frequency triaxial device was also used to study the effects of high frequency vibration that exists in the ground motions of eastern Canada. The test results show the following:

1). The shear modulus degradation of the fly ash can be described by the hyperbolic strain model. The parameters for the model obtained from the cyclic simple shear tests agree well with those from the resonant column tests. Under cyclic triaxial loading state, however, the shear modulus degrades less rapidly than under the cyclic simple shear loading state.

2). The liquefaction resistance of the fly ash at loose state is stronger than a loose volcanic soil and a loose silt, possibly due to a high friction angle in the fly ash.

3). At 1 Hz loading, the cyclic triaxial test gives a higher liquefaction resistance than the cyclic simple shear test.

4). The cyclic triaxial test gives a higher strength at 10 Hz than at 1 Hz.

5). The energy approach is applicable for assessing liquefaction resistance of the fly ash.

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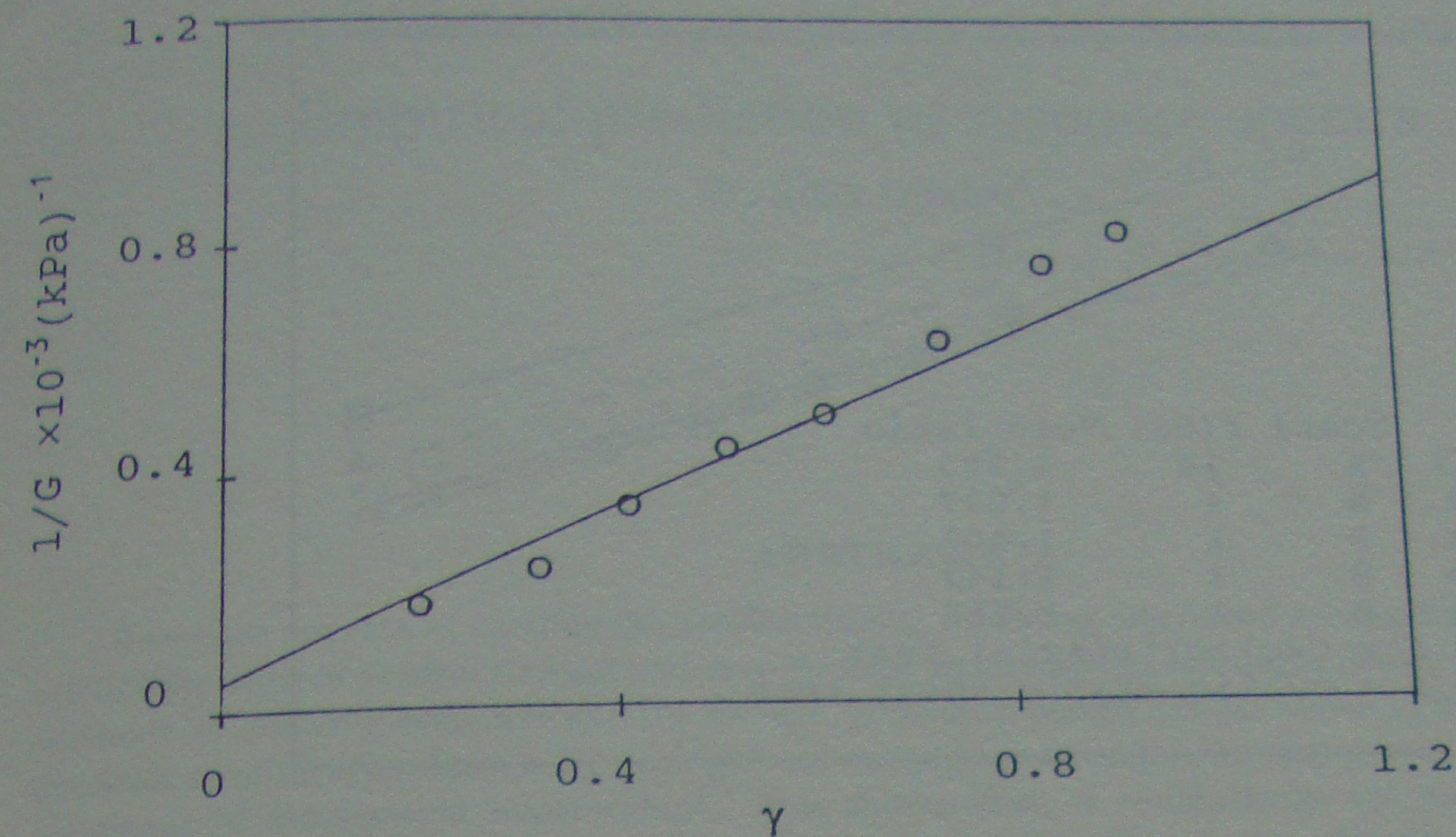

Figure 1. 1/G vs γ from cyclic simple shear test at a consolidation pressure of 50 kPa

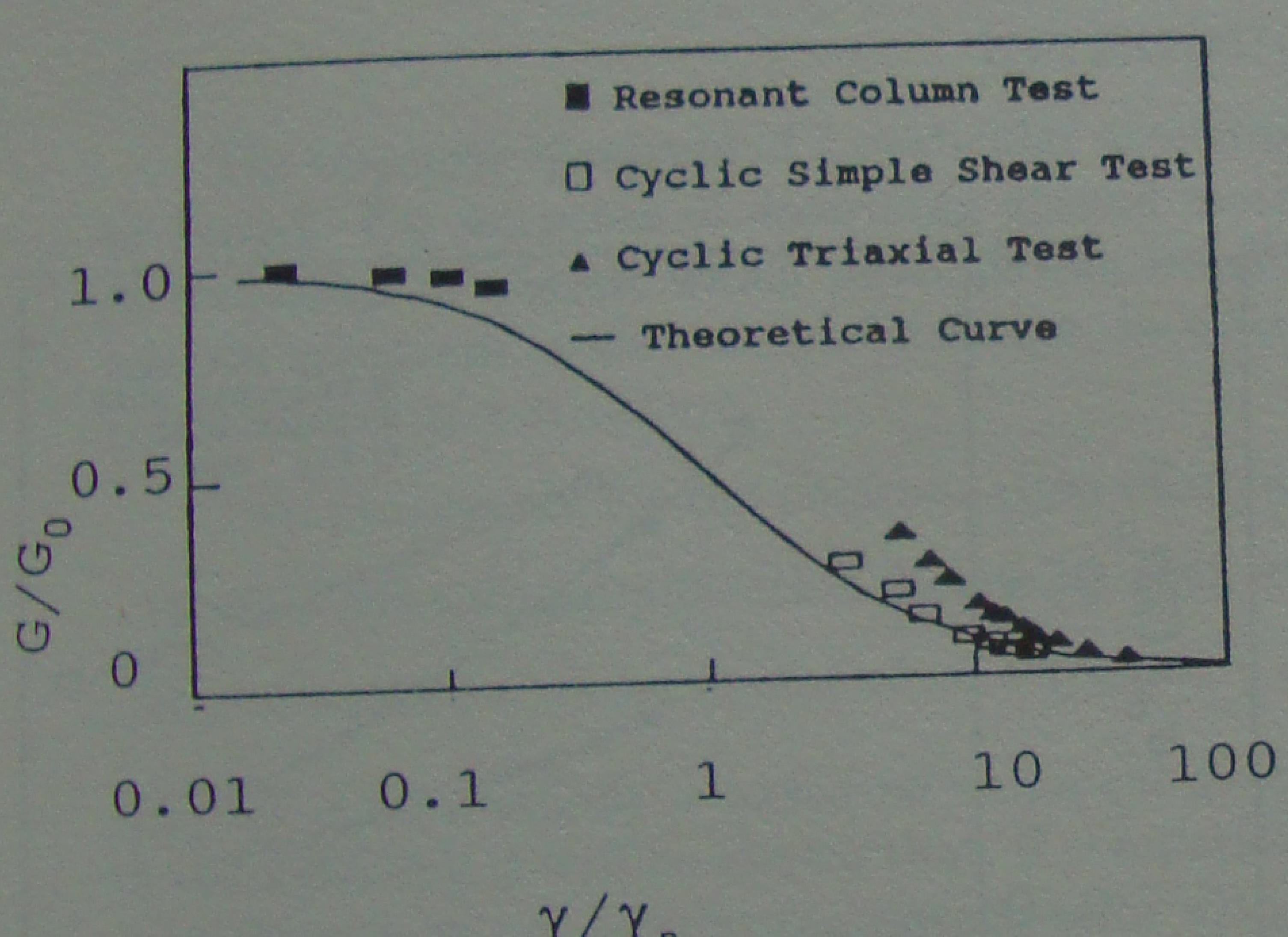

Figure 2. Comparison of modulus degradation from different tests

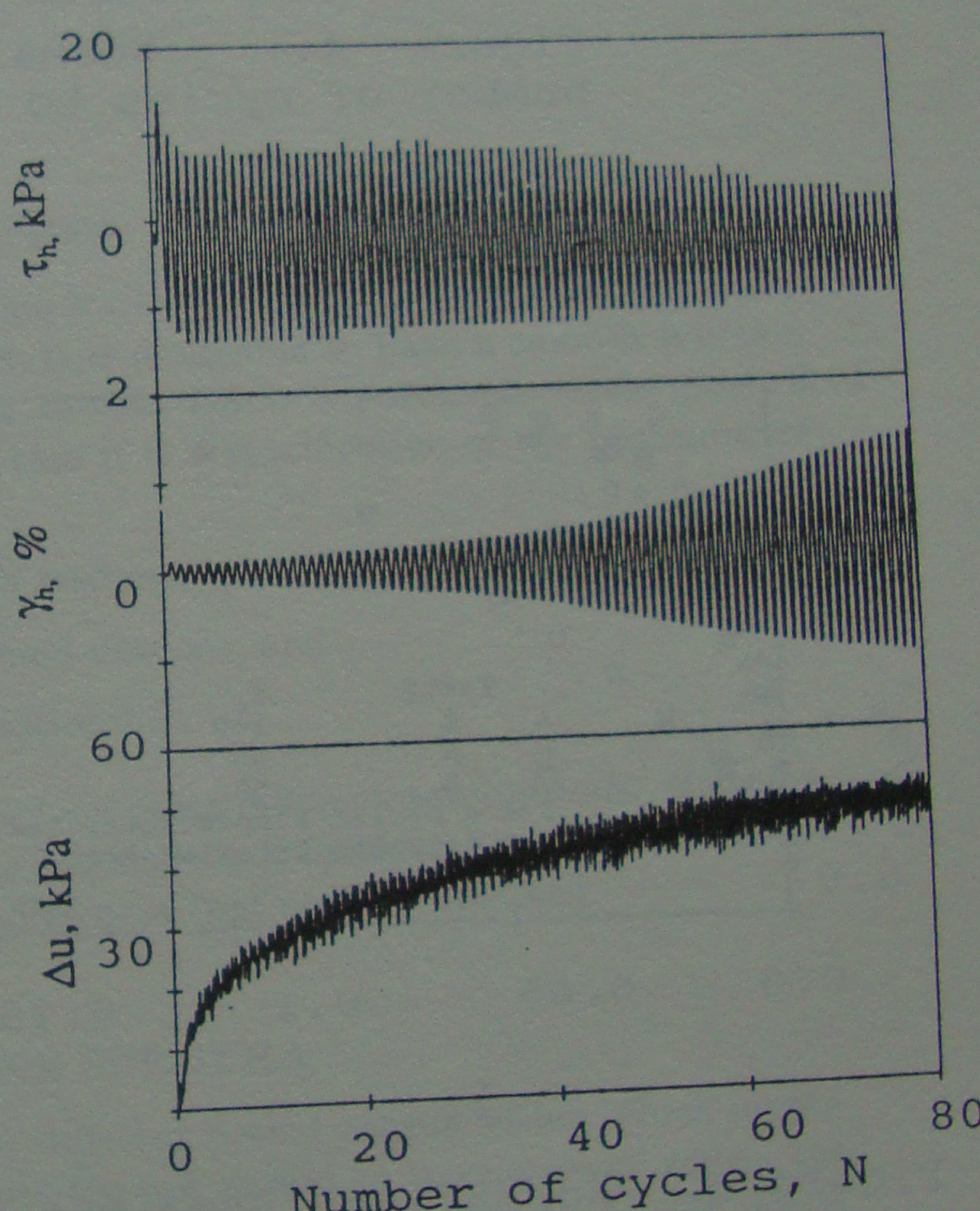

Figure 3. Typical horizontal stress (τ_h), horizontal strain strain (γ_h) and excess pore water pressure(Δu)

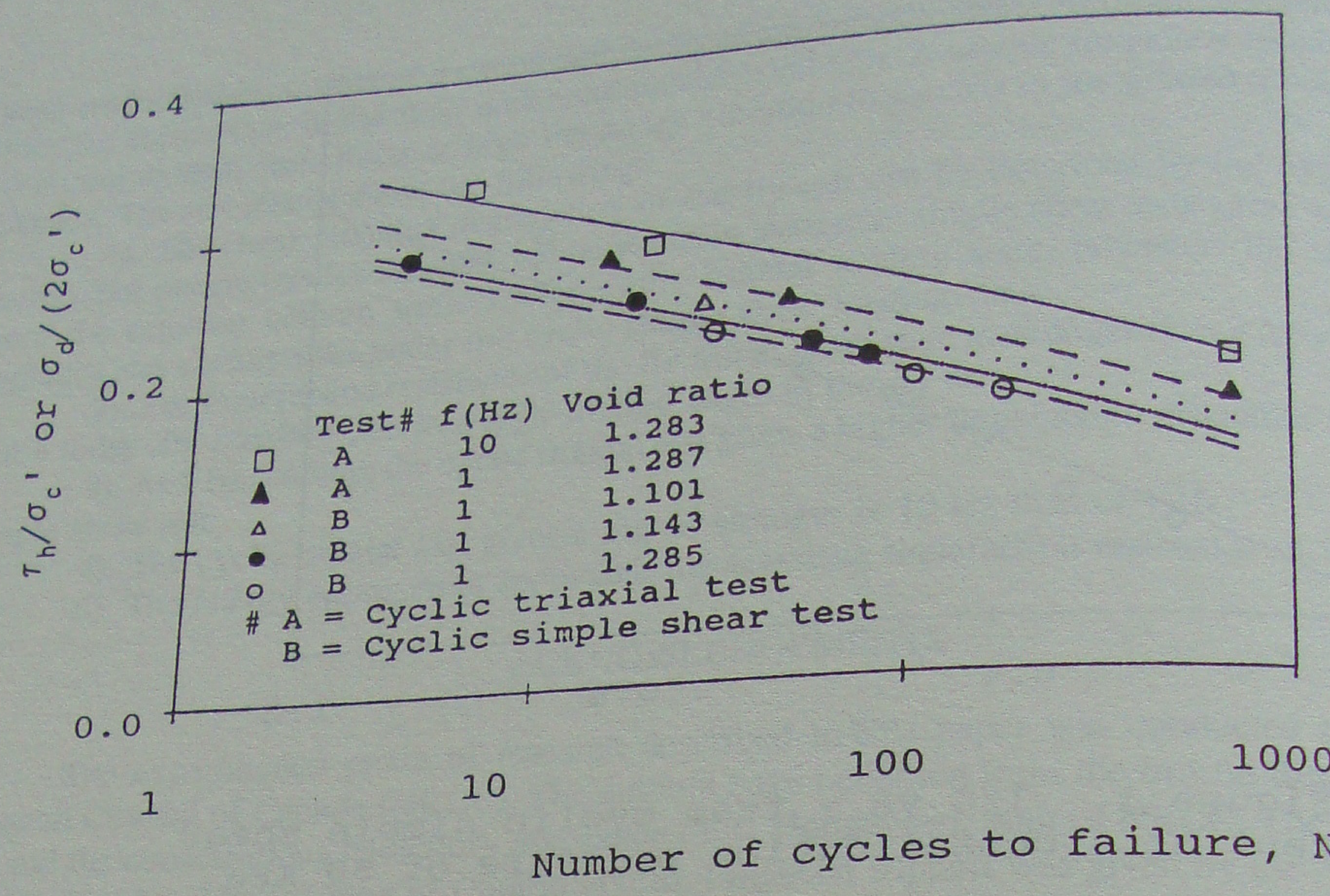

Figure 4. Normalized liquefaction resistance vs number of cycles to failure

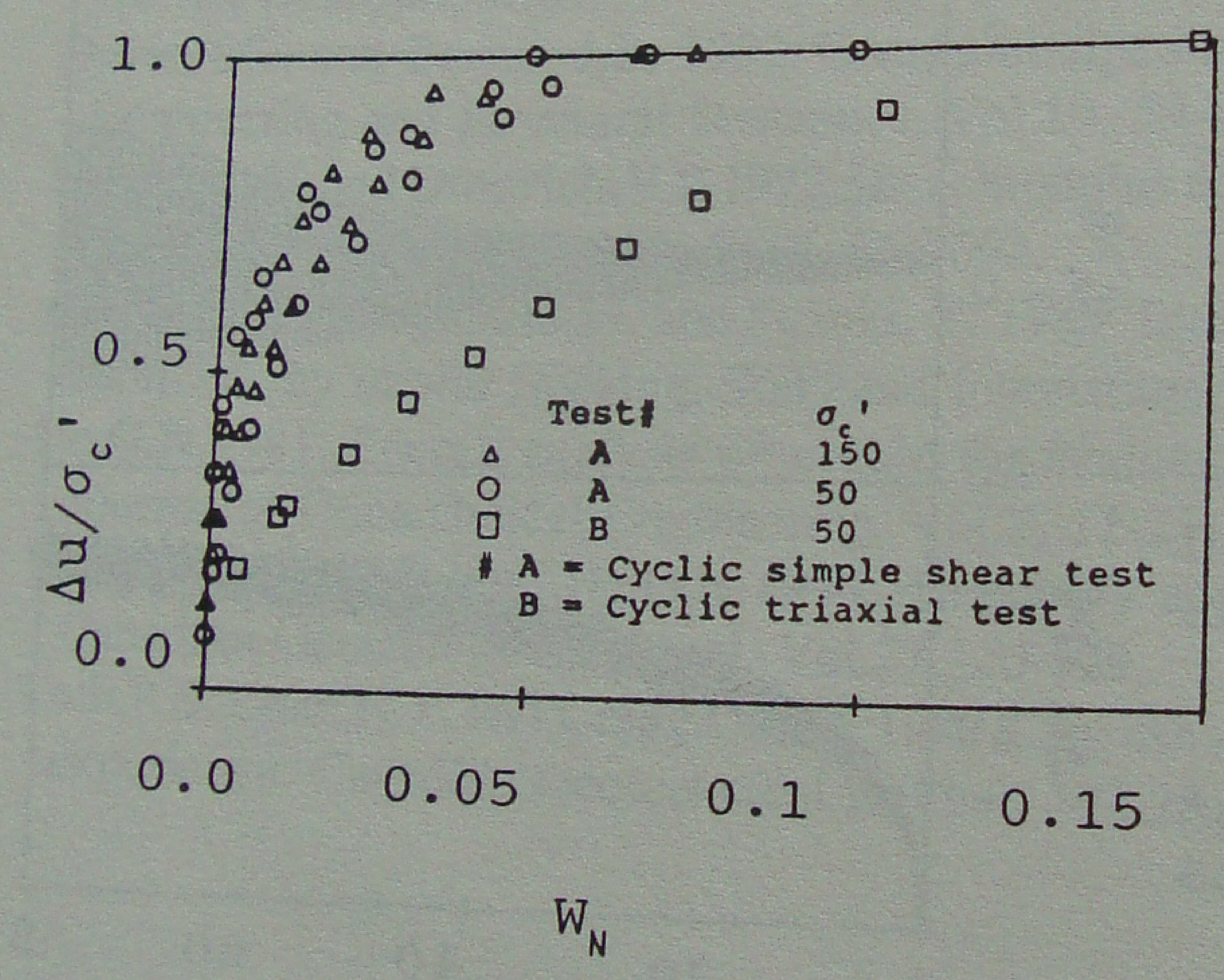

Figure 5. Normalized pore water pressure ($\Delta u/\sigma_c'$) vs normalized dissipated energy (W_N)

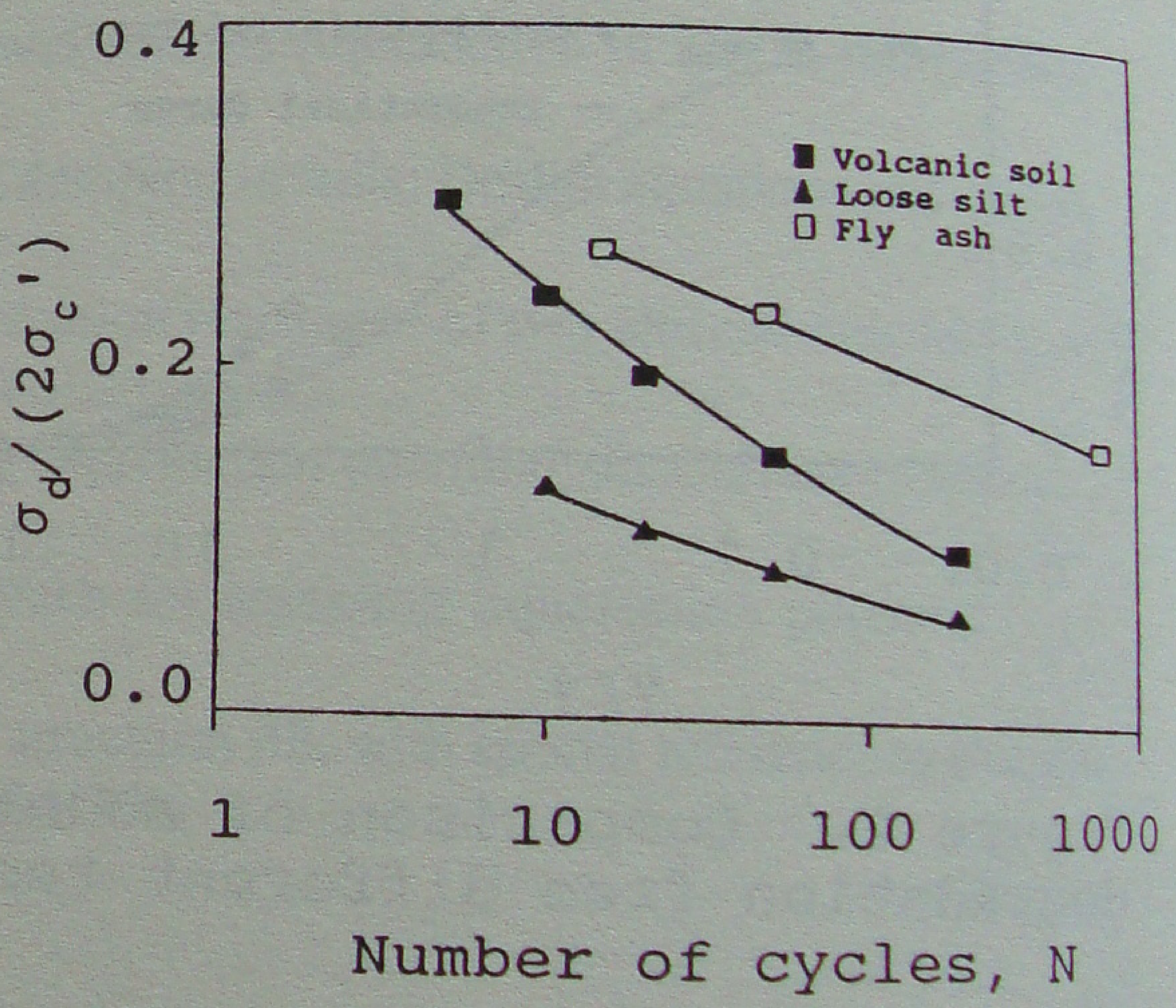

Figure 6. Comparison of liquefaction resistance of different loose soils