International Workshop on Uncertainties in Nonlinear Soil Properties and their Impact on Modeling Dynamic Soil Response

Sponsored by the National Science Foundation and PEER-Lifelines Program

PEER Headquarters, UC Berkeley, March 18-19, 2004

Plenary Session 2: Status of Soil Testing and Material Models

Emerging Trends in Dynamic Simple Shear Testing

by

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Geotechnical test results are the most fundamental component of practically any geotechnical analysis. Their validity and accuracy define the validity and accuracy of the analysis. Soil material properties determined in the laboratory or in the field represent the foundation of geotechnical analyses and design procedures. The laboratory and field test data also form the basis for studies of spatial variability of soil properties and various probabilistic approaches to asses the uncertainties in determining soil parameters. Accordingly, if there are fundamental aspects of the cyclic stress-strain behavior of soil that have not been tested, or have not been tested adequately or accurately enough, their testing will impact and improve the modeling of dynamic soil response in a truly fundamental manner.

A domain of cyclic soil behavior that needs to be fully explored is the small-strain cyclic soil behavior. In spite of numerous studies in last 15 years (e.g., Jamiolkowski et al., 1999; Shibuya et al., 1994) there are still fundamental small-strain behavior issues that remain to be resolved. In the last 15 years standard triaxial, torsional and simple shear devices have been continuously improved and modified for cyclic small-strain testing purposes. Many of these modifications are very complex and have taken advantage of most current technologies of parameter measurements and data processing. At the same time, the resonant column device, which has been used for the testing of shear moduli and damping at very small strains since its introduction decades ago, has been also used extensively (e.g., Kim et al. 1991; Stokoe et al., 1995, 1999). The resonant column device has been used either alone or in combination with torsional shear device.

Another domain of cyclic soil behavior that has not been adequately investigated is the cyclic stress-strain behavior at very large cyclic strains. Although this kind of testing does not require complicated modifications of testing devices, the data available in the literature are surprisingly scarce.

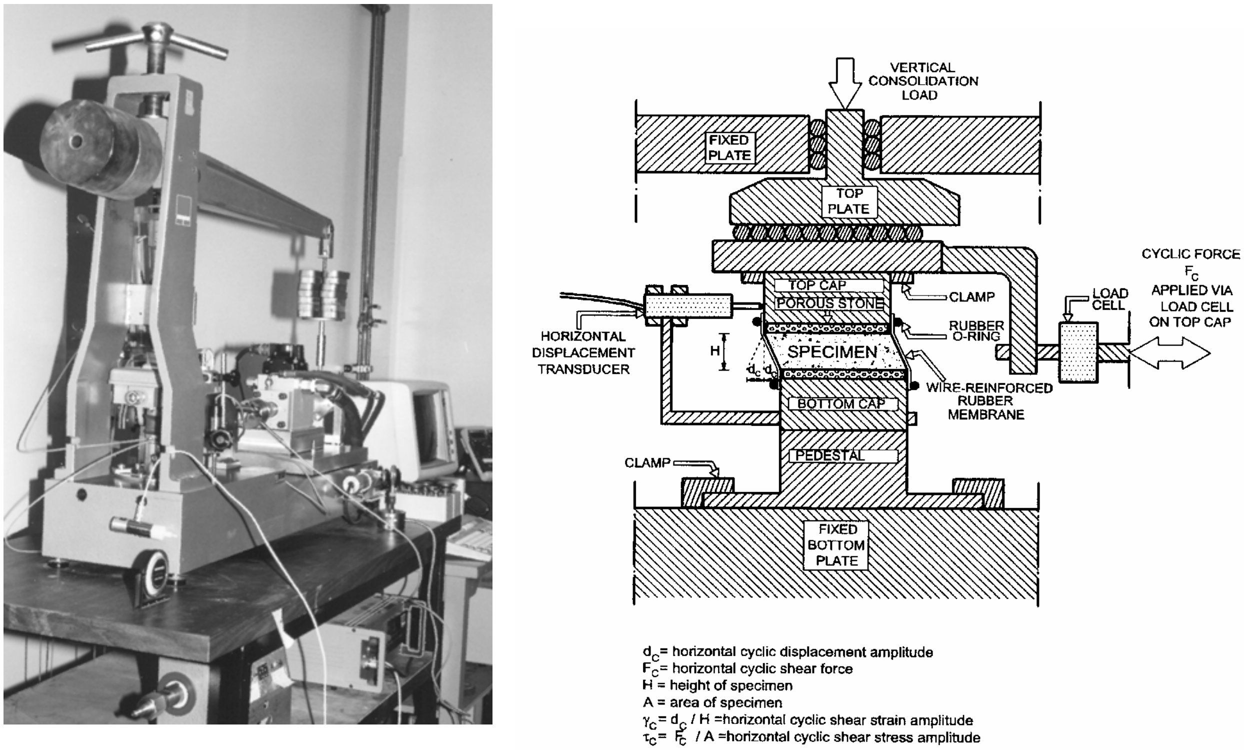

Fig. 1 NGI-type direct simple shear device at the UCLA Soil Dynamics Laboratory

To investigate the unresolved fundamental aspects of the cyclic stress-strain behavior at very small and very large cyclic shear strain amplitudes, γ_c, a long-term testing effort using simple shear devices has been undertaken at UCLA. This effort encompasses many different soils. The NGI-type concept of direct simple shear (DSS) device with circular specimen confined in a wire-reinforced rubber membrane has been used (Bjerum and Landva, 1966). Either constant-volume equivalent-undrained, or cyclic settlement NGI-type DSS tests were conducted.

Because small-strain properties cannot be accurately tested in the standard, commercially available NGI-type simple shear device shown above in Fig. 1, a new simple shear device for small-strain cyclic testing was designed and built at UCLA in 1993 (Doroudian and Vucetic, 1995). The new testing apparatus is shown in Fig 2. It is called the dual-specimen direct simple shear (DSDSS) device. The most unique feature of the DSDSS device is that two specimens of the same soil are tested simultaneously; instead of just one as usually is the case in geotechnical laboratory practice. This special configuration, in conjunction with very stiff components of the device and non-contact displacement transducers, enables almost complete elimination of problems associated with undesirable false deformations, system compliance and friction. Furthermore, the cyclic horizontal displacement is applied manually (in a “quiet” manner) on the middle cap between the specimens, thus avoiding undesirable vibrations that would be introduced by hydraulic, pneumatic or electrical motor. As a result, very small strains and stresses could be applied and measured accurately in a controlled manner. As shown in Fig. 3, cyclic loops can be recorded clearly at γ_c= 0.001%. Other DSDSS results confirm that cyclic loops can be recorded comfortably at γ_c as small as 0.0003% (Doroudian and Vucetic, 1998; Matesic and Vucetic, 2003; Vucetic and Tabata, 2003).

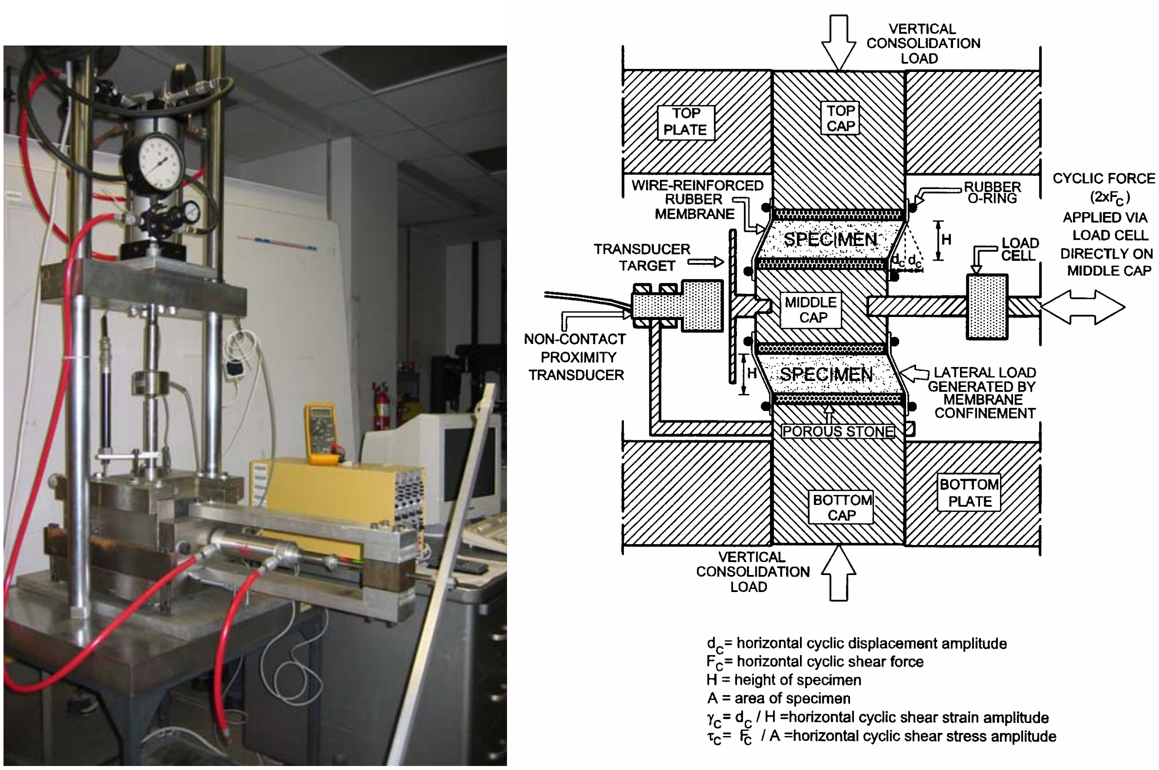

Fig. 2 UCLA Dual-specimen direct simple shear device – DSDSS device

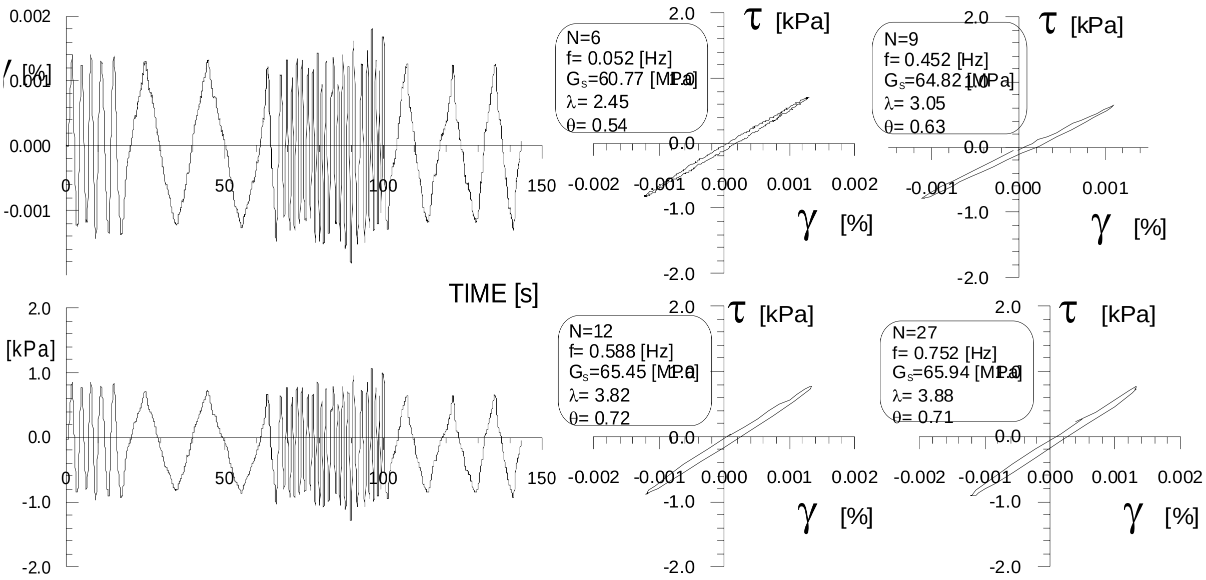

Fig. 3 Typical results of variable-frequency cyclic DSDSS test on clay (Matesic and Vucetic, 2003)

The large-strain cyclic simple shear tests have been conducted in both the standard DSS device shown in Fig. 1 and the DSDSS devices. An example of typical results obtained in the standard DSS device is shown below in Fig. 4.

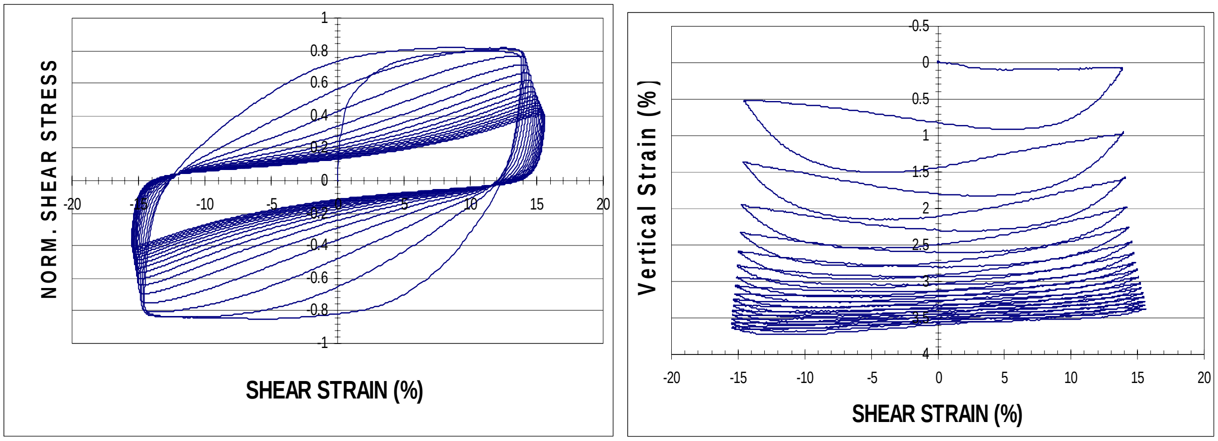

Fig. 4 Typical large-strain cyclic behavior of low-plasticity clay in the standard DSS device; cyclic shear strain amplitude, γ_c= 15.00% (Hsu and Vucetic, 2002)

The long-term goals of the cyclic DSS and DSDSS testing at UCLA are illustrated in Fig. 5. They include the refinement and extension of the data on secant shear modulus, G_s, and equivalent viscous damping ratio, λ, into the domains of very small shear strains well below the volumetric cyclic threshold shear strain, γ_{tv}, and very large cyclic shear strains between $\gamma_c \approx$ 1.0% and 15.0%. In the context of these long term goals, extensive studies on the magnitude of γ_{tv} for different soils and its correlation to the soil's plasticity index, PI, have also been conducted. More specifically, the values of γ_{tv} for cyclic settlement, cyclic stiffness degradation and equivalent pore water pressure have been investigated separately with the help of DSS and DSDSS devices. The entire long-term investigation at UCLA has been going on for more that 10 years and it has encompassed cyclic testing in different research projects supported by different institutions, such as NSF, University of California Office of the President, Lawrence Livermore National Laboratory, Caltrans, PEER, Southern California Earthquake Center (SCEC), and the Okinawa International Exchange and Human Resources Development Foundation in Japan.

Over 160 cyclic tests were conducted on more than 60 soils. Given such a wide scope of the long-term study, and the fact that in the small-strain DSDSS tests many cycles of loading can be applied repeatedly under different conditions without altering the specimen microstructure, very large amounts of cyclic stress-strain data have been generated. To analyze and compare these data systematically, a conveniently structured database with a cyclic loop as its elementary unit has been developed (Hsu and Vucetic, 2002). In the database every cyclic loop in each test is characterized by a series of parameters such as, plasticity index, PI, void ratio, e, degree of saturation, S, vertical stress, σ_v, cyclic shear strain amplitude, γ_c , secant shear modulus, G_s, damping ratio, λ, frequency, f, shape of applied cyclic shear strain, etc. The main power of the database is that very large number of cyclic loops and their characteristics can be compared and manipulated between different tests in various ways, thus enabling the creation and instant graphical presentation of many useful behavioral trends and comparisons. The data points from the most comprehensive study are presented below in Fig. 6. The modulus reduction and damping curves derived from this data points are presented in Fig. 7. It can be seen that both the

G_s and λ data cover the range of γ_c from 0.0003% to 15% in large quantities, while as shown in Fig. 6 quite a few data were recorded even below 0.0002%. From such a wealth of data several truly fundamental aspects of the cyclic stress-strain behavior have been analyzed. Many findings have been published while some are in the process of being published; some available data are still being analyzed, while some aspects of the cyclic behavior are just being tested.

The list of investigated research subjects, corresponding publications, and current research needs are summarized in Table 1. Specific research subjects that need to be studied are identified. The subjects for which significant raw data are available and need to be systematically processed and thoroughly analyzed are also identified.

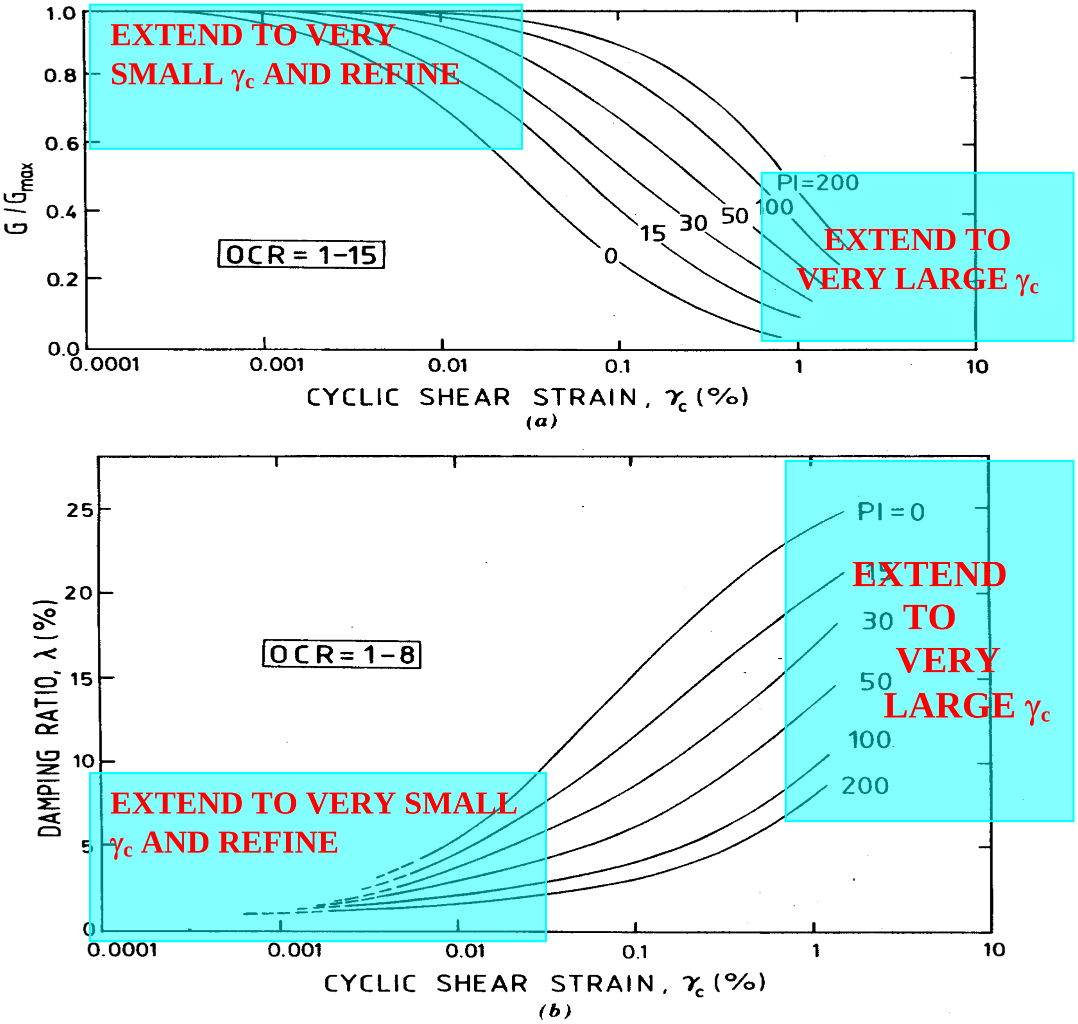

Fig. 5 Average secant shear modulus reduction (G_s/G_{max} versus γ_c) and damping (λ versus γ_c) curves suggested by Vucetic and Dobry (1991) with domains that have been investigated at UCLA (Hsu and Vucetic, 2002)

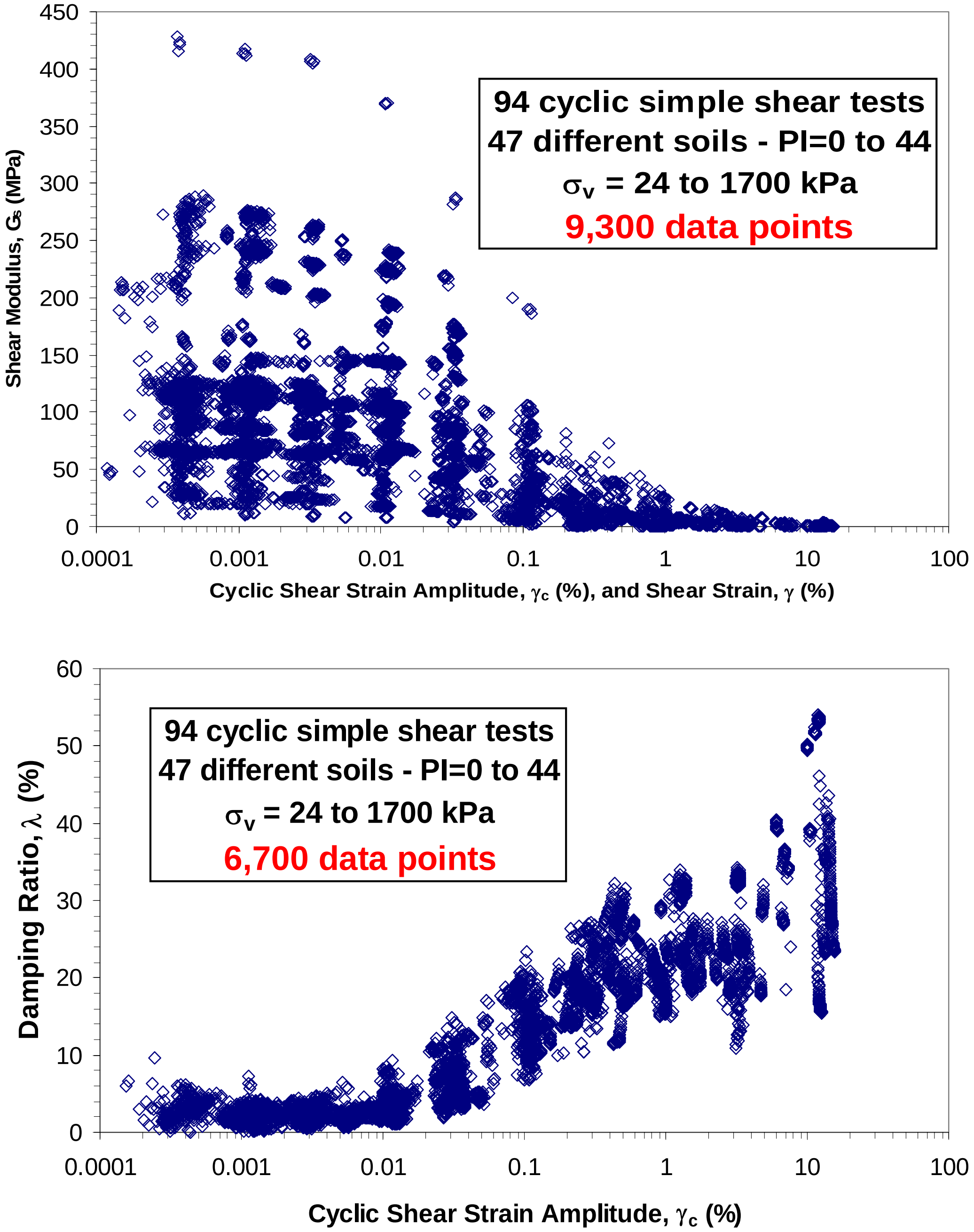

Fig. 6 Cyclic-loop data points of G_s and λ from the most comprehensive UCLA study (Hsu and Vucetic, 2002)

In the following paragraphs and figures some selected but limited research results are presented. Although these results are relevant for the modeling of seismic soil response, they may not be the most important, because one of the reasons for showing them is to illustrate the capabilities of the DSS and DSDSS testing.

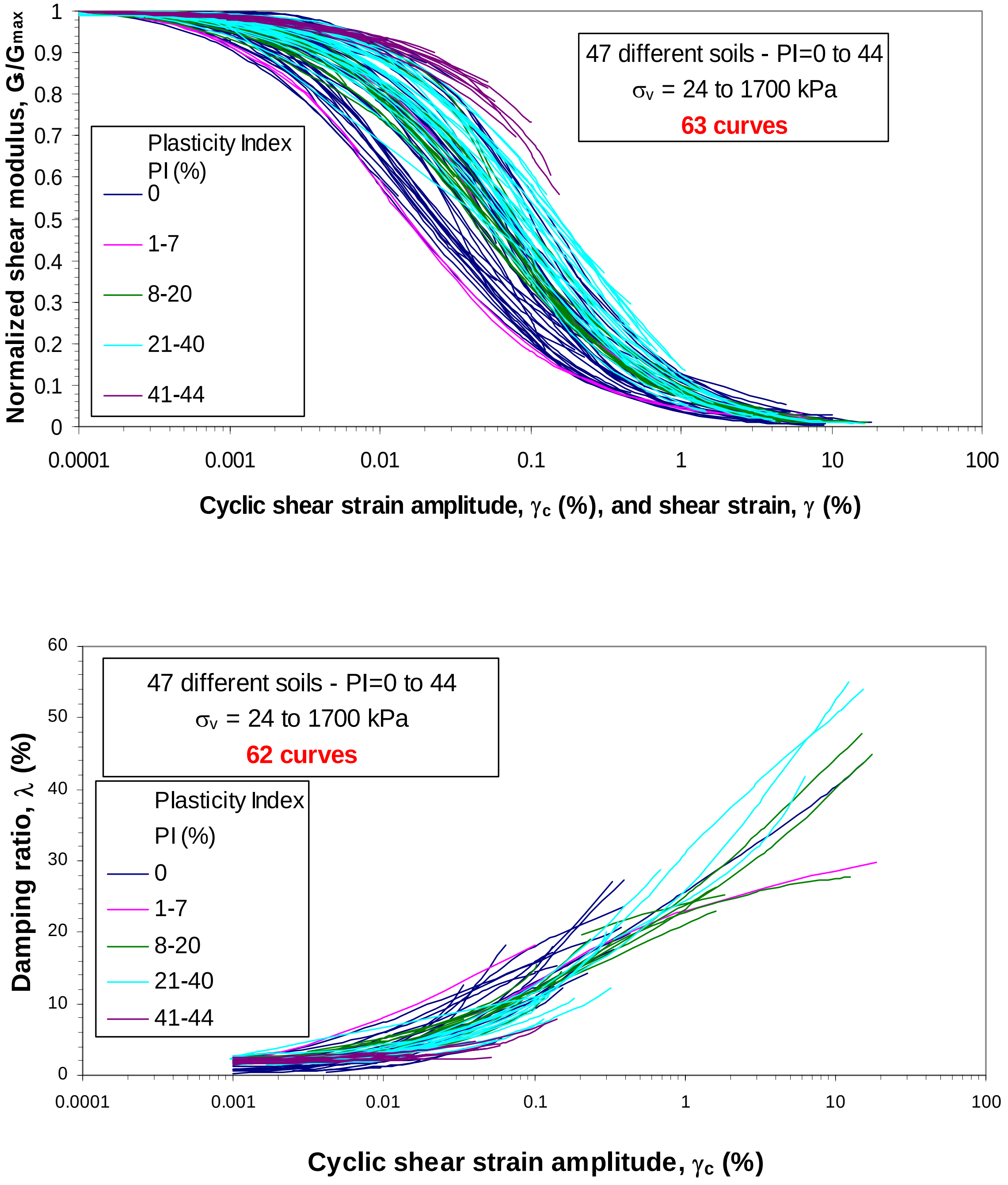

Fig. 7 Modulus reduction and damping curves derived from the data points presented in Fig. 6 (Hsu and Vucetic, 2002)

Table 1. Research subjects investigated at UCLA, corresponding publications and research needs

GENERAL RESERCH TOPICS	SPECIFIC RESEARC SUBJECTS	MAJOR PUBLICATIONS AND THE STATUS OF UNPUBLISHED DATA AND RESEARCH NEEDS
SECAN SHEAR MODULUS, G_s	Degree of nonlinearity and precise shape of G_s-log γ_c and G_s/G_{max}-log γ_c curves at small strains	Hsu and Vucetic (2002) Lanzo and Vucetic (1999a) Lanzo, Vucetic and Doroudian (1997) Matesic and Vucetic (2003) **- Existing data need analysis**
	Effect of vertical stress, σ_v, and overconsolidation ratio, *OCR*, on the shape of G_s-log γ_c and G_s/G_{max}-log γ_c curves at small strains	Hsu and Vucetic (2002) Lanzo, Vucetic and Doroudian (1997)
	Effect of frequency of cyclic loading, *f*, and average strain rate, dγ/dt, on the shape of G_s-log γ_c and G_s/G_{max}-log γ_c curves at small strains	Matesic and Vucetic (2003) Vucetic, and Tabata (2003) Vucetic, Tabata and Matesic (2003)
	Effect of the frequency of cyclic loading, *f*, and average strain rate, dγ/dt, on G_{max} at small strains	Hsu and Vucetic (2002) Tabata (2004) **- More research needed**
	Extension of G_s-log γ_c and G_s/G_{max}-log γ_c curves to very large strains	Hsu and Vucetic (2002) **- More research needed**
DAMPING RATIO, λ	Effect of plasticity index, *PI*, on damping ratio curve, λ-log γ_c, at very small γ_c	Hsu and Vucetic (2002) Lanzo and Vucetic (1999a,b) Vucetic, Lanzo and Doroudian (1998a)
	Effect of vertical stress, σ_v, and overconsolidation ratio, *OCR*, on damping ratio curve, λ-log γ_c, at very small γ_c	Hsu and Vucetic (2002) Vucetic, Lanzo and Doroudian (1998a) **- Existing data need** analysis
	Effect of the shape of applied cyclic shear straining (triangular versus sinusoidal versus trapezoidal, stc.) on damping ratio, λ, and damping curve, λ-log γ_c, at small γ_c	Hsu and Vucetic (2002) Lanzo and Vucetic (1999b) Vcetic, Lanzo and Doroudian (1998a, b) **- Existing data need analysis**
	Effect of the frequency of cyclic loading, *f*, and average strain rate, dγ/dt, on damping ratio, λ, and damping curve, λ-log γ_c, at small γ_c	Lanzo and Vucetic (1999a) Lanzo, Doroudian and Vucetic (1999) Tabata (2004) **- More research needed**
	Damping ratio, λ, and damping curve, λ-log γ_c, at very large cyclic strain amplitudes, γ_c	Hsu and Vucetic (2002) **- More research needed**

RELATIONSHIP BETWEEN MONOTONIC AND CYCLIC STRESS-STRAIN BEHAVIOR	Comparison between the cyclic and monotonic stress-strain behavior: (a) validity of Masing rules, and (b) comparison between the G_s/G_{max}-log γ_c curves obtained from cyclic and monotonic tests	Hsu and Vucetic (2002) Tabata (2004) **- More research needed**
	Effects of the magnitude and variation of strain rate, dγ/dt, on the monotonic stress-strain behavior and its relation to cyclic small-strain behavior	Tabata (2004) **- More research needed**
VOLUMETRIC CYCLIC THRESHOLD SHEAR STRAIN, γ_{tv}	Volumetric cyclic threshold shear strain, γ_{tv}, for cyclic settlement, including the effects of *PI* and σ_v	Hsu and Vucetic (2004)
	Volumetric cyclic threshold shear strain, γ_{tv}, for cyclic stiffness degradation, including the effects of *PI* and σ_v	**- Submitted for publication**
	Volumetric cyclic threshold shear strain, γ_{tv}, for equivalent cyclic pore water pressure in NGI-type DSS cyclic test, including the effects of *PI* and σ_v	Hsu and Vucetic (2002) **- Submitted for publication**
SOIL TESTING ISSUES	Effect of sample disturbance on Gs, G_{max} and λ, and the G_s/G_{max}-log γ_c and λ-log γ_c curves	**- Comprehensive research needed**
	Effect of the lateral stress mobilization in NGI-type DSS test on cyclic stress-strain properties	**- Comprehensive research needed**

Effect of average strain rate $\dot{\gamma} = d\gamma/dt$ on G_s and G_s -log γ_c trend

The effects of the frequency of cyclic loading and corresponding strain rate have been extensively investigated. The effect of the higher frequency, f, and corresponding average strain rate, $\dot{\gamma} = d\gamma/dt$ =4 f γ_c, on G_s is commonly quantified by the strain-rate shear modulus parameter:

$$\alpha_G = \frac{\Delta G_s}{\Delta \log \dot{\gamma}} = \frac{(G_S)_{\text{high-}f} - (G_S)_{\text{low-}f}}{\log \dot{\gamma}_{\text{high-}f} - \log \dot{\gamma}_{\text{low-}f}} = \frac{(G_S)_{\text{high-}f} - (G_S)_{\text{low-}f}}{\log \dfrac{\dot{\gamma}_{\text{high-}f}}{\dot{\gamma}_{\text{low-}f}}}.$$

Parameter α_G describes the increase of G_s for the tenfold (one order of magnitude) increase of $\dot{\gamma}$. If α_G is normalized by some convenient reference G_s, the strain-rate shear modulus factor, $N_{\dot{\gamma}-G}$, is obtained:

$$N_{\dot{\gamma}-G} = \frac{(G_s)_{\text{high-}f} - (G_s)_{\text{low-}f}}{\log \dfrac{\dot{\gamma}_{\text{high-}f}}{\dot{\gamma}_{\text{low-}f}}} \frac{1}{(G_s)_{\text{ref}}} = \frac{\alpha_G}{(G_s)_{\text{ref}}}.$$

Factor $N_{\dot{\gamma}-G}$ was introduced by Isenhower and Stokoe (1981) and it describes the relative increase of G_s for the tenfold increases of $\dot{\gamma}$ with respect to a reference G_s. In this respect, $N_{\dot{\gamma}-G}$ is more convenient for quantifying the rate effects than α_G. Figure 8a below shows how the G_s-γ_c data points are scattered vertically at certain levels of γ_c for a clay if $\dot{\gamma}$ varies significantly. Figure 8b-e shows further how G_s increases consistently with $\dot{\gamma}$ at the same levels of γ_c. Finally, Fig. 9 presents the trends of α_G and $N_{\dot{\gamma}-G}$ with γ_c for different soils. For example, it can be seen in Fig. 9b that G_s in clays tested at γ_c =0.001% increases by 4-8% for a tenfold increase of $\dot{\gamma}$. At smaller γ_c =0.0005% this increase is even larger, between 7 and 11%.

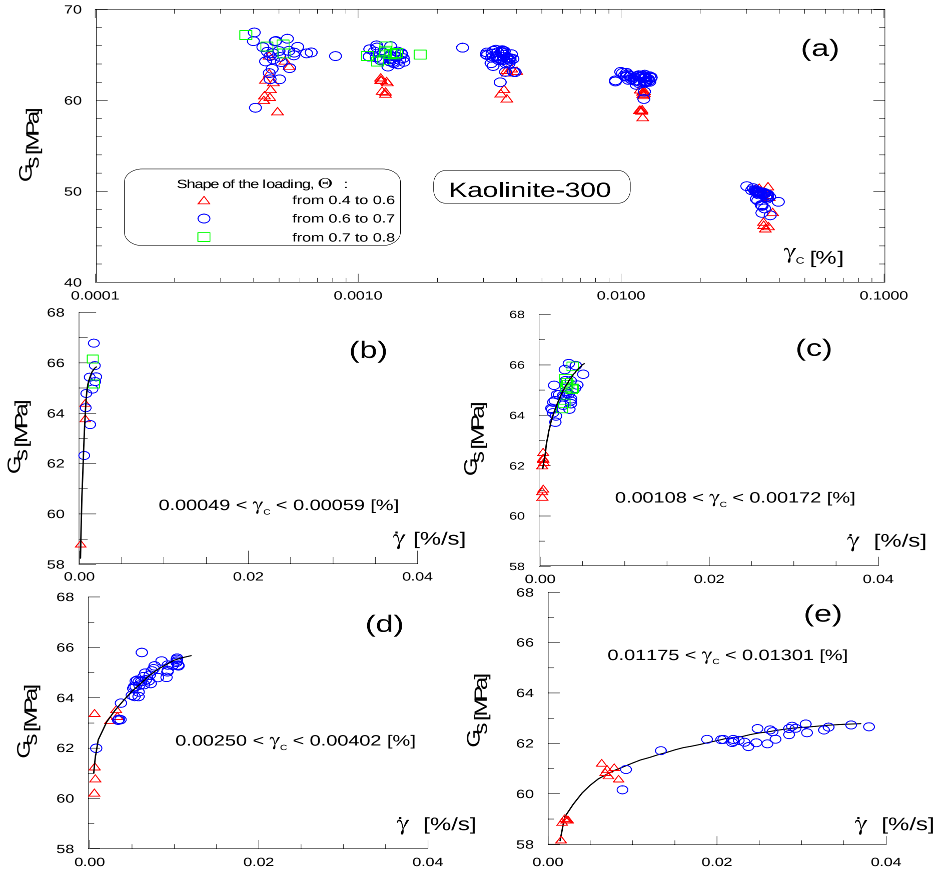

Fig. 8 Influence of $\dot{\gamma}$ on G_s for a clay (Matesic and Vucetic, 2003)

Such a strong effect of $\dot{\gamma}$ on G_s indicates that the shape of the G_s/G_{max}-log γ_c curve at small strains depends significantly on the values of the applied $\dot{\gamma}$ and corresponding frequencies, f. This effect can produce different curvatures of the G_s/G_{max}-log γ_c curves at small strains, and in this way it can affect drastically the outcome of a site response study. For example, under otherwise regular testing conditions, a G_s/G_{max} =1.0 curve representing a perfectly linear soil can be obtained easily at very small strains if at all levels of γ_c the tests are conducted at the same frequency, f. This and other effects of $\dot{\gamma}$ on G_s and their ramifications are described in detail in Matesic and Vucetic (2003) and Vucetic and Tabata (2003).

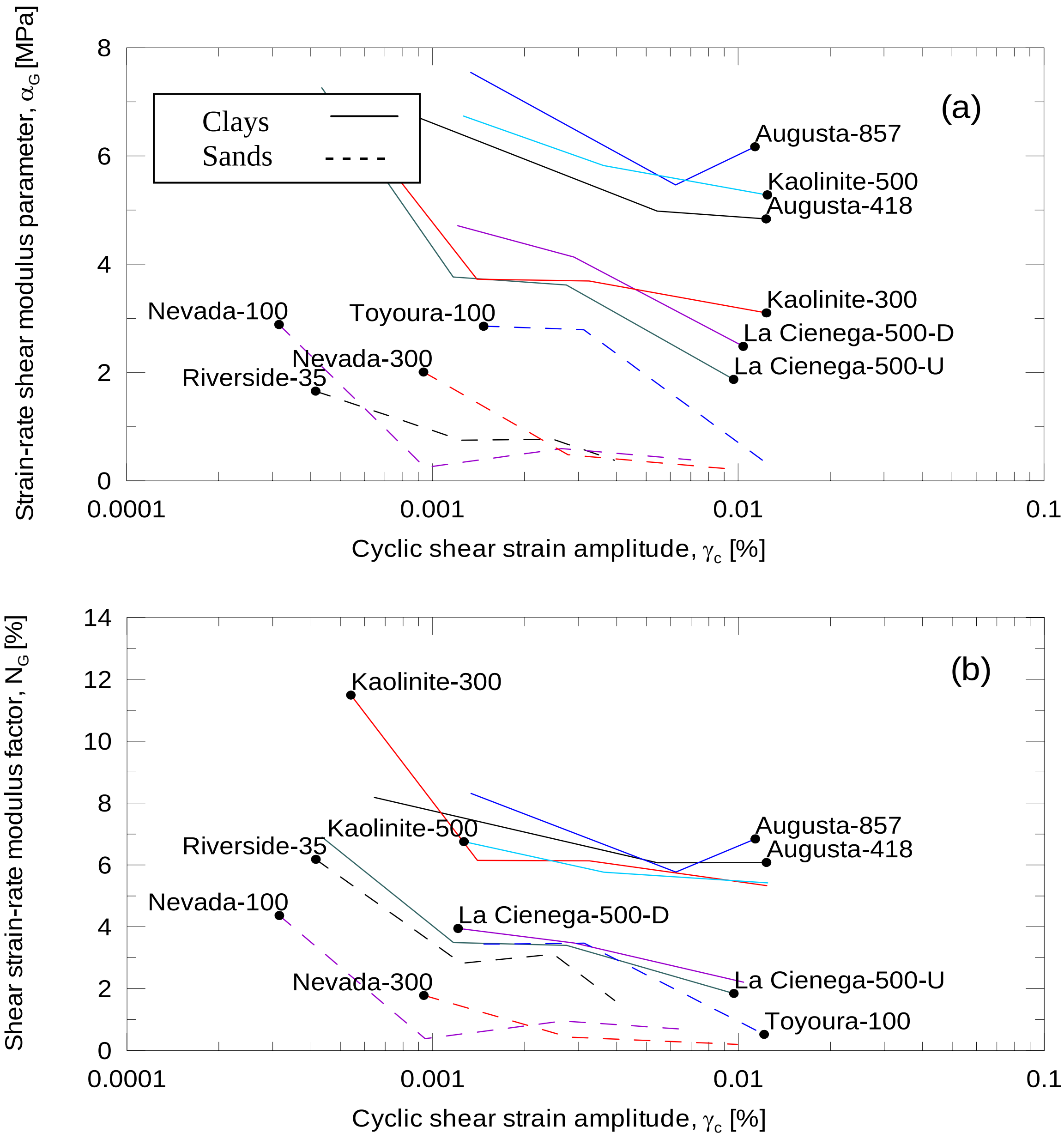

Fig. 9 Trends of α_G and $N_{\dot{\gamma}-G}$ with γ_c for several sands and clays (Matesic and Vucetic, 2003)

Effect of frequency, f, on damping ratio λ

The data obtained in the DSDSS device reveal that the effect of frequency, f, on damping ratio λ and λ-log γ_c curve is more intricate than previously concluded by others on the basis of limited testing. In Fig. 10 below, this effect is shown for one high plasticity clay. It can be seen that below f = 0. 1 Hz damping ratio λ decrease with f, while above f = 0. 1 Hz it increases. For other soils somewhat different trend has been obtained. This trend also depends on the shape of cyclic straining. Finding out the precise effect of frequency, f, and corresponding average strain rate, $\dot{\gamma} = d\gamma/dt$, on damping ratio λ can substantially improve the modeling of soil response, because it is well known that the site response depends strongly on the magnitude of λ.

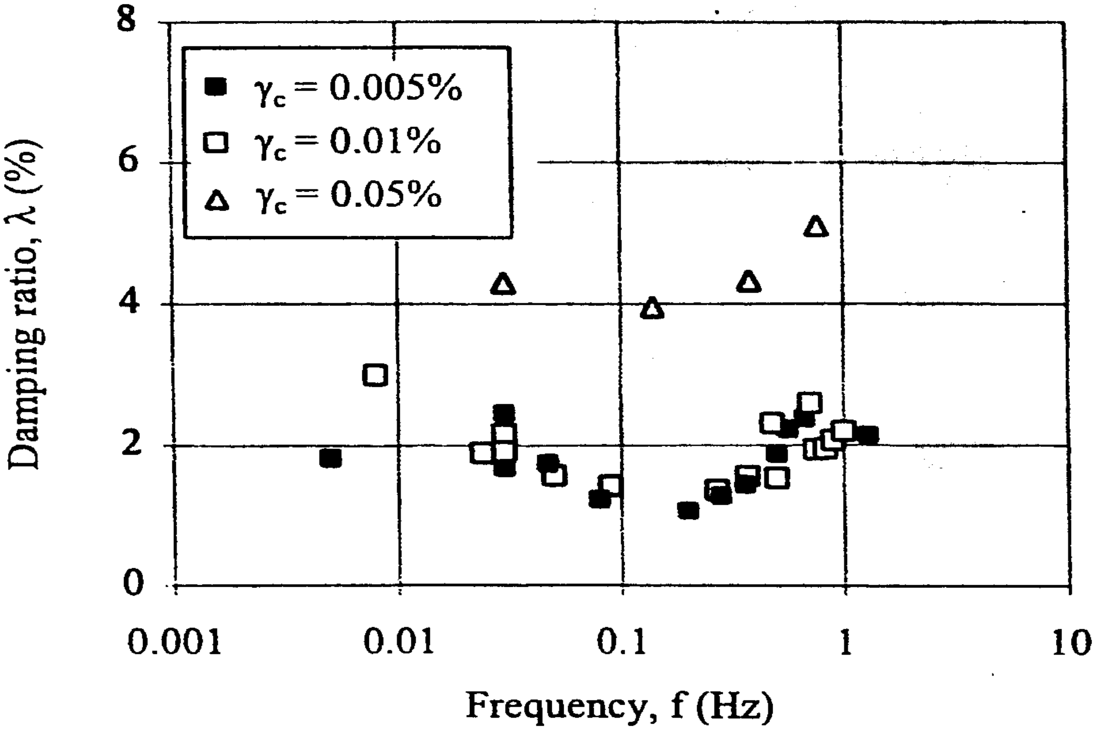

Fig. 10 Effect of frequency, f, on damping ratio λ (Lanzo and Vucetic, 1999a; Lanzo, Doroudian and Vucetic 1999)

Volumetric cyclic threshold shear strain, γ_{tv}, for cyclic settlement

The trend of the volumetric cyclic threshold shear strain for cyclic settlement with the plasticity index, PI, is shown below in Fig 11. While considerable data on γ_{tv}, for cyclic settlement of sands were published before by others, the data on clayey soil have been scarce. A literature review has revealed only three γ_{tv} values for cyclic settlement of clay, most likely because of the complexity and high cost of such experimental efforts. Besides that, these three results show no trend with PI. Figure 12 shows furthermore that γ_{tv} levels correspond to surprisingly large G_s

reduction of 55 to 80%. Construction of Fig. 12 was made possible by testing both γ_{tv} and G_s on the same soils, which seems to be the only such combined experimental study to date.

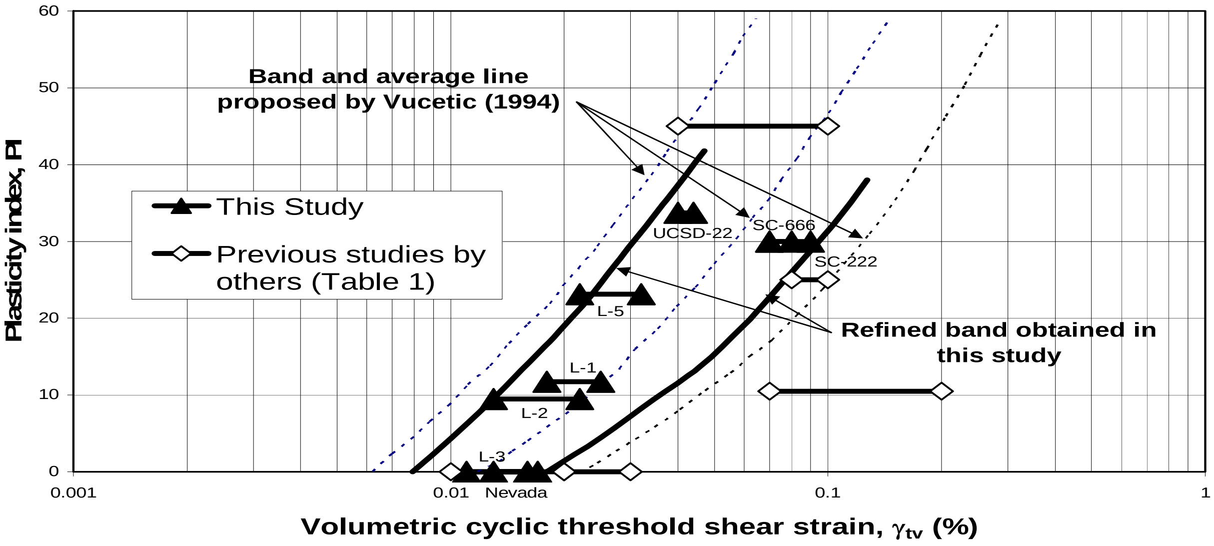

Fig. 11 Trend of volumetric cyclic threshold shear strain, γ_{tv}, for cyclic settlement with plasticity index, PI (Hsu and Vucetic, 2004)

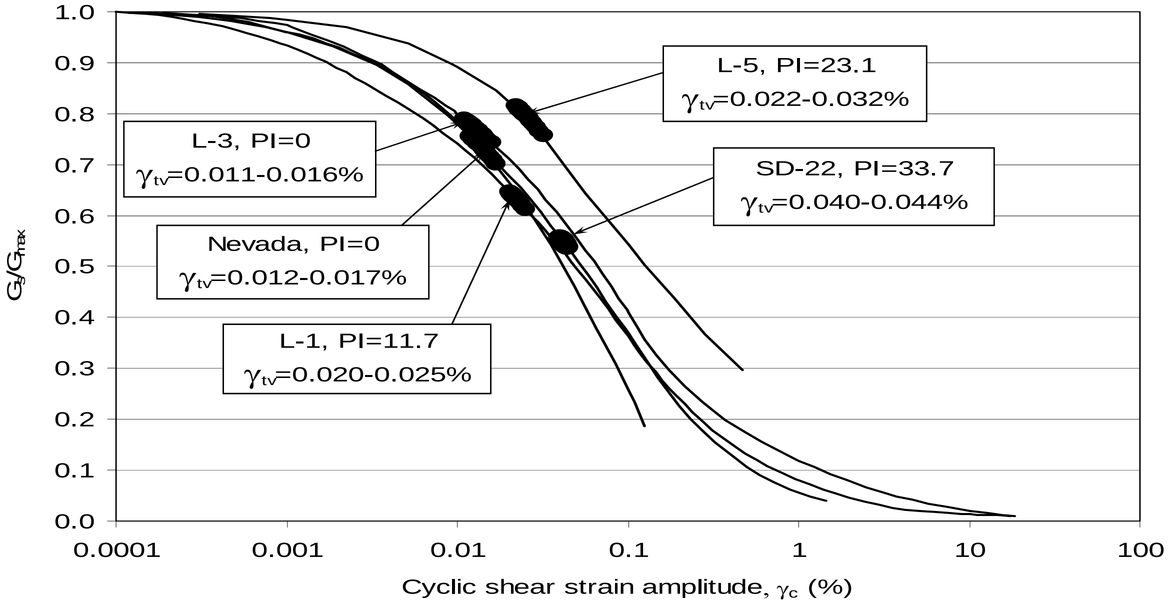

Fig. 12 Location of the γ_{tv} points on the G_s/G_{max}-log γ_c curves (Hsu and Vucetic, 2004)

Conclusions

The main conclusion is that some fundamental aspects of the cyclic stress-strain behavior of soils are still not known or understood to a satisfactory extent, in spite of the fact that the outcome of dynamic site response analysis depends primarily on the soil properties. Accordingly, the investigations of certain fundamental aspects of the cyclic stress-strain behavior need to be conducted. These investigations can be conducted in the range of larger cyclic shear strains with the help of standard cyclic simple shear device, and in the range of small cyclic shear strains with the help of UCLA dual-specimen direct simple shear device.

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