26 May 2010, 4:45 pm - 6:45 pm

Development of Database of Cyclic Soil Properties from 94 Tests on 47 Soils

Leo Matesic
University of Rijeka, Croatia

Chu-Chung Hsu
University of California, Los Angeles, CA

Marco D'Elia
DMS Geotechnical Eng. Srl, Italy

Mladen Vucetic
University of California, Los Angeles, CA

Fifth International Conference on
Recent Advances in Geotechnical Earthquake Engineering and Soil Dynamics
and Symposium in Honor of Professor I.M. Idriss
May 24-29, 2010 • San Diego, California

DEVELOPMENT OF DATABASE OF CYCLIC SOIL PROPERTIES FROM 94 TESTS ON 47 SOILS

Leo Matesic
Faculty of Civil Engineering
University of Rijeka, Rijeka
and Geokon-Zagreb
Croatia

Chu-Chung Hsu
Civil and Environmental Eng.
University of California,
Los Angeles, California 90095
USA

Marco D'Elia
DMS Geotechnical Eng. srl
Via San Lucio, 25
00165 Rome
Italy

Mladen Vucetic
Civil and Environmental Eng.
University of California
Los Angeles, California 90095
USA

ABSTRACT

Cyclic properties of 47 soils were tested in several investigations between 1994 and 2004 in the standard Norwegian Geotechnical Institute (NGI) direct simple shear (DSS) device and an NGI-type dual-specimen DSS (DSDSS) device for small strain testing. In each investigation many cycles of different amplitude, γ_c, and frequency, f, were applied at different levels of vertical stress, σ_v, and overconsolidation ratio, OCR. In DSDSS device many consecutive series of different small γ_c=0.0003-0.01% were applied on the same specimens without changing their structure, because at such small γ_c cyclic shearing is nondestructive. Consequently, the vast amounts of small-strain data were generated. This necessitated the development of new approach to data processing and analysis. New procedure for reading, checking, organizing, combining, comparing and analyzing the vast arrays of cyclic test data has been developed and structured into a database that has the cyclic loop as its elementary unit. Each cyclic loop in the database is characterized by the soils' plasticity index, moisture content, void ratio, degree of saturation, σ_v, OCR, γ_c, f, secant shear modulus, damping ratio, and the shape of cyclic straining. Using the database very large number of cyclic loops can be compared to instantly obtain graphical presentation of different behavioral trends. The structure of the database and its application is summarized.

INTRODUCTION

Many soil dynamics analyses consider cyclic behavior of soil in pure shear. An example is the behavior of soil at level horizontally layered ground due to vertically propagating seismic shear waves presented in Fig. 1. Under such conditions soil element is on top of the normal vertical and horizontal consolidation effective stresses, σ'_v and σ'_h, existing before the earthquake, subjected to shear stresses, τ, caused by the earthquake. The main feature of such a behavior and the cyclic loading behavior in general are the cyclic stress-strain loops the properties of which need to be known to perform the soil dynamics analysis. The characterization of cyclic loop is presented in Figs. 2 and 3. The loop is typically characterized by its cyclic shear strain amplitude, γ_c, cyclic shear stress amplitude, τ_c, secant shear modulus, G_s, maximum shear modulus, G_{max}, and the equivalent viscous damping ratio, λ, that depends on its thickness. In any given soil dynamics event these parameters depend on the: (i) soil type that can be characterized by the classification properties such as the grain size distribution and Atterberg limits, among which the plasticity index, PI, seems to be the most descriptive, (ii) density and corresponding void ratio, e, (iii) moisture content, w, (iv) degree of saturation, S, (v) consolidation stresses σ_v and σ_h, (vi) overconsolidation ratio, OCR, (vii) frequency of cyclic loading, f, and (viii) the shape of cyclic straining (cyclic strain versus time) that is typically sinusoidal but can vary between triangular and trapezoidal.

CYCLIC TESTING

Between 1994 and 2004, in a soil dynamics laboratory of the University of California, Los Angeles (UCLA), a series of investigations of cyclic soil properties listed above was carried out (Doroudian and Vucetic, 1999; Hsu and Vucetic, 1998; 1999; Matesic and Vucetic, 1998; Tabata and Vucetic, 2000; 2002; Vucetic, 2000; Vucetic et al., 1998; 1999). In these investigations the following two types of tests were conducted in two direct simple shear (DSS) devices, (i) the constant volume equivalent undrained test aimed at investigating the behavior of fully saturated soils in undrained conditions, and (ii) the variable volume test to investigate the cyclic compression of unsaturated soils (volume change due to cyclic loading). Both DSS devices were of the Norwegian Geotechnical Institute (NGI) type where specimens are enclosed in a wire reinforced rubber membrane that greatly restricts and almost prevents lateral strains during consolidation and shear. One device was the standard NGI DSS devices shown in Fig. 4 that was originally introduced by Bjerrum and Landva (1966). The other was an NGI-type dual-specimen DSS (DSDSS) device for small strain testing shown in Fig. 5 that was designed and built at UCLA by Doroudian and Vucetic (1995; 1998). The standard NGI DSS device was employed to investigate the cyclic properties in the range of moderate to large γ_c between approximately 0.1% and 10%. In the DSDSS device the cyclic properties over the wide range of γ_c between approximately 0.0003% and 10% were investigated, with a focus on very small to small strains between 0.0003% and 0.1%.

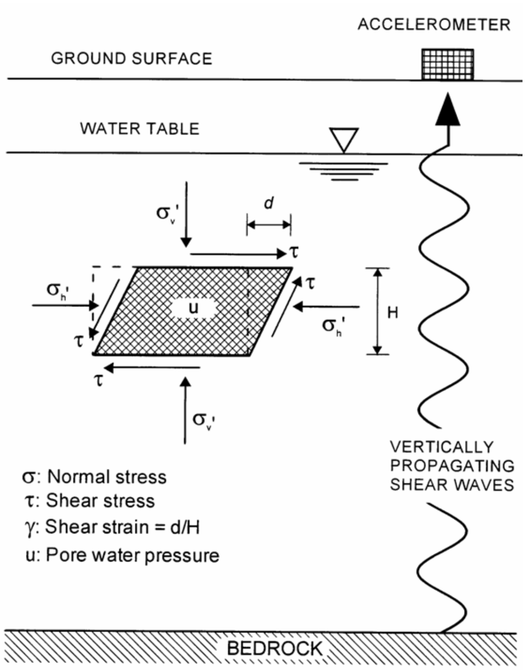

Fig. 1. Idealized stress-strain conditions of soil element at horizontally layered level ground due to vertically propagating seismic shear waves

The investigations at UCLA between 1994 and 2004 encompassed 47 soils that were tested in 94 tests, most of which were cyclic strain-controlled with constant γ_c. Many tests were conducted in several stages where γ_c was constant in each stage but varied from stage to stage. In the DSDSS device in particular, many consecutive series of different small γ_c between 0.0003 and 0.01% were applied on the same set of two specimens without changing their structure, because at such small γ_c below the cyclic threshold shear strain (Dobry et al., 1982; Vucetic, 1994; Hsu and Vucetic, 2004; 2006) the cyclic shearing is nondestructive. To optimize the outcome of the investigations even further, in each stage of DSDSS test the cyclic testing parameters were often varied, such as shown in Fig. 7 where the frequency of cyclic straining, f, was varied. It should be mentioned that in this figure and some other figures θ is the strain-time history shape parameter defined by Vucetic et al. (1998) that measures the effect of the shape of cyclic straining on λ.

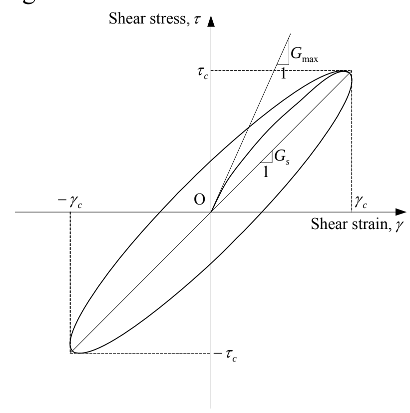

Fig. 2. Idealized fully closed initial cyclic stress-strain loop (first 1.25 cycles) with definition of cyclic shear strain amplitude, γ_c, cyclic shear stress amplitude, τ_c, secant shear modulus, G_s, and maximum shear modulus, G_{max}

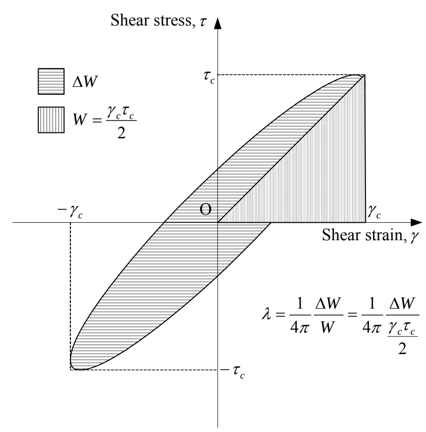

Fig. 3. Definition of the equivalent viscous damping ratio, λ

DATABASE OF CYCLIC SOIL PROPERTIES

From the above description of the testing it is evident that vast amounts of data were collected during the investigations of cyclic soil properties, in particular during the small-strain nondestructive cyclic testing with the DSDSS device in which the conditions and parameters such as γ_c, σ_v, f, and θ can be changed repetitively on a single pair of specimens without affecting their integrity and hence the integrity of the parameters measured. Such a convenience not only stimulated but necessitated the development of a new innovative approach to data processing, analysis and sharing that takes advantage of today's fast computers and sophisticated software. Consequently, a new procedure for reading, checking, organizing, combining, comparing and analyzing the vast arrays of cyclic test data was developed. The main product of this procedure is a conveniently structured database with a cyclic loop as its elementary unit. In the database, each cyclic loop is characterized by a series of parameters such as PI, e, w, S, σ_v, OCR, γ_c, τ_c, f, G_s, θ and λ.

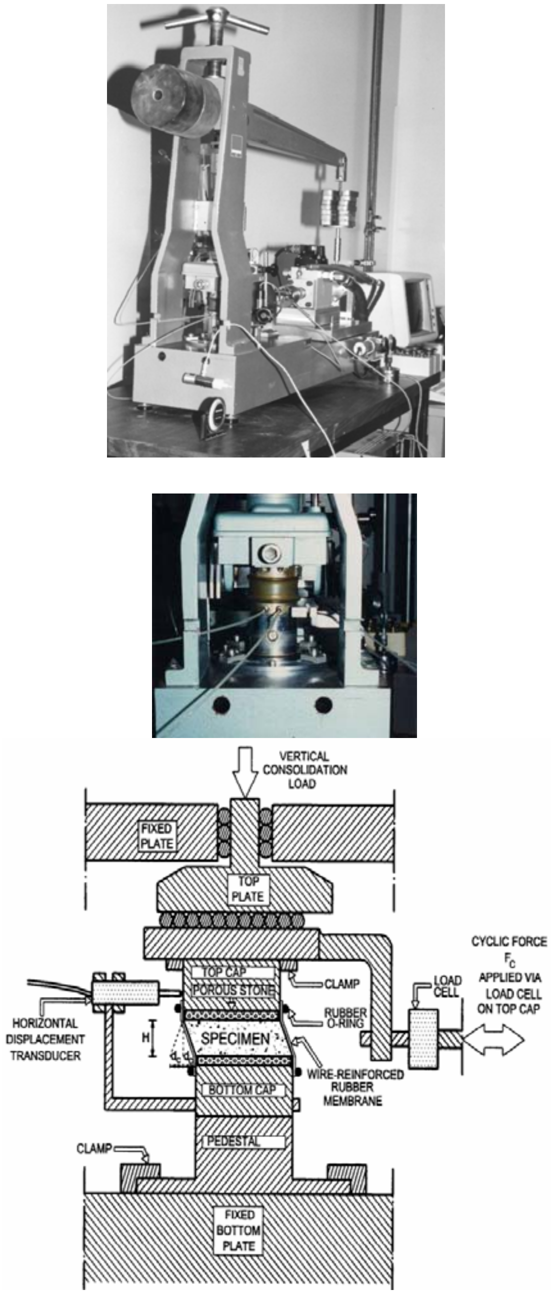

Fig. 4. Standard NGI direct simple shear (NGI DSS) apparatus (introduced by Bjerrum and Landva,1966)

The main premise of the database is that cyclic loops obtained following different cyclic loading paths are very similar, basically the same, as long as they pertain to the same PI, e, w, S, σ_v, OCR, γ_c, f, and θ. It is thus presumed that cyclic behavior parameters of these loops, such G_s and λ, are almost identical, which has been verified and is pretty much correct. The power of such database is that very large number of cyclic loops from many different tests and their characteristics can be compared and manipulated in various ways, thus enabling the creation and instant graphical presentation of many useful behavioral trends and comparisons.

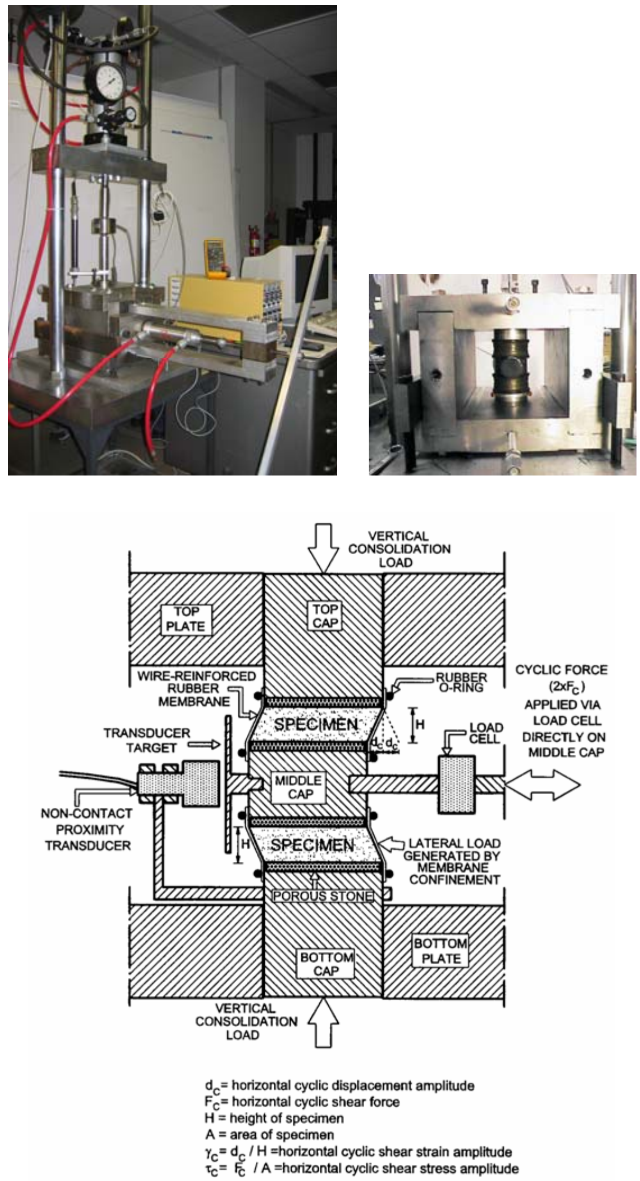

Fig. 5. NGI type of dual-specimen direct simple shear (NGI DSDSS) apparatus for small-strain testing (Doroudian and Vucetic, 1995; 1998)

The "Microsoft Access" database software was employed to develop the database the structure of which is rather complex. It includes 10 separate tables and over hundred fields with the characteristics of cyclic loops that are linked and can be related to each other. The structure of the database is shown in Fig. 6. In spite of its complexity, the database is rather flexible and relatively easy to use. Using the customized "Microsoft Excel" worksheets the database is also easily maintainable and updateable with the data from new tests.

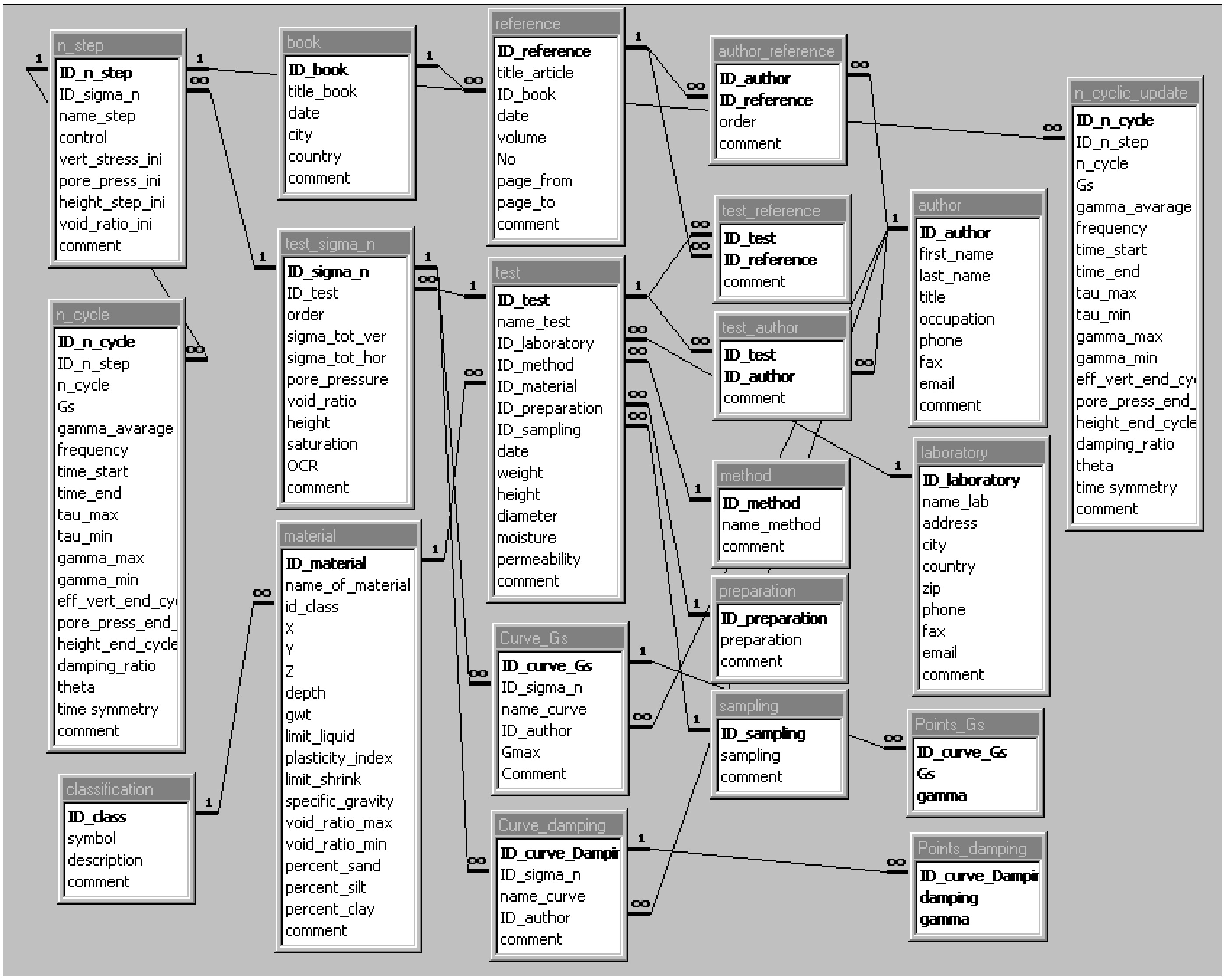

Fig. 6. The structure of the UCLA database of cyclic soil properties the elementary unit of which is the cyclic stress-strain loop

The input of the recorded test data into the database and its utilization consists of the following four consecutive steps: (i) identification and inspection of the cyclic stress-strain loops recorded during the testing and digitized by the data acquisition system, (ii) organization of the relevant raw data into the "Microsoft Excel" worksheet files, (iii) input of the data into the database, and (iv) manipulation and automatic graphical presentation of the data with “Microsoft Excel”. These steps are somewhat elaborate, in particular the first step, and their description is beyond the scope of this database summary. They are described in relative detail in Hsu and Vucetic (2002).

The database was designed not just for handling the simple shear test results generated at UCLA, but also to accommodate the results of other types of tests that can be gathered from the literature.

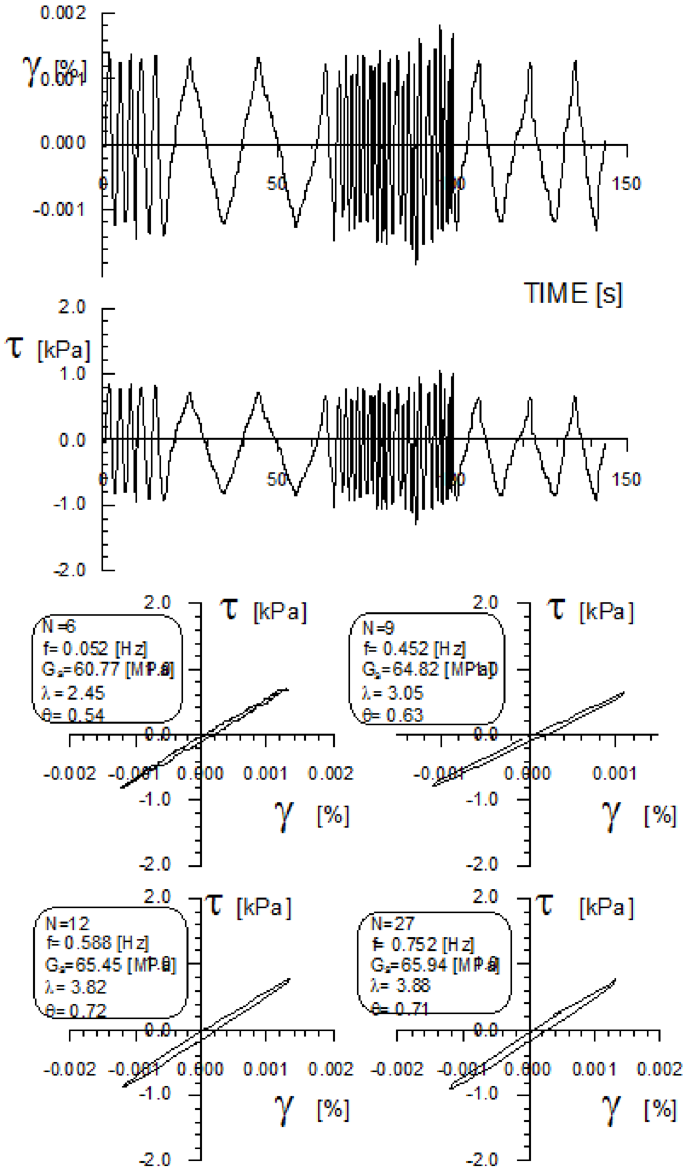

Fig. 7. Typical results from one cyclic stage of DSDSS test on Kaolinite clay (PI=20, σ'$_{vc}$=300 kPa, OCR=1.0) aimed at investigating the effects of cyclic frequency and average rate of straining at very small cyclic strains (data treated in Matesic and Vucetic,2003; Vucetic and Tabata, 2003; Vucetic et al., 2003)

PRESENTATION OF SOME DATA AND EXAMPLES OF THEIR MANIPULATION AND COMPARISOSNS

Currently, only the UCLA simple shear test results have been included into the database. To date over 120 cyclic DSS and DSDSS tests were conducted at UCLA on more than 60 soils, yielding enormous amounts of data. The results in this paper, however, encompass only 94 tests on 47 different soils that are represented in the data base with around 10,000 cyclic loops, i.e., by approximately 10,000 data points. Below are some examples of plots and charts generated automatically or semi-automatically from this part of the database.

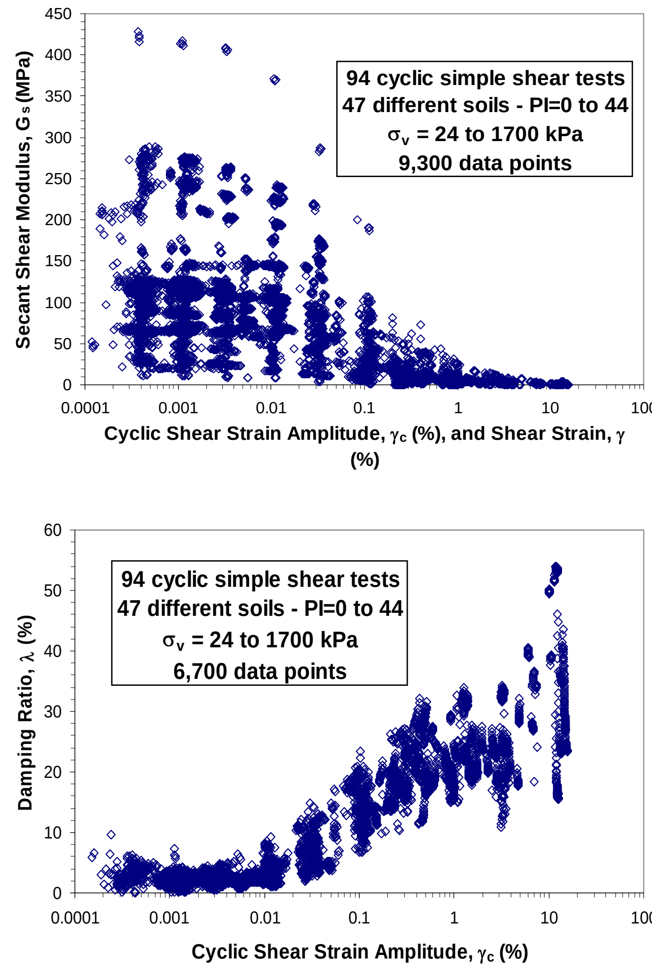

Fig. 8. Distribution of the secant shear modulus and damping ratio data points with the logarithm of cyclic shear strain amplitude retrieved from the database of cyclic soil properties – each data point pertains to a cyclic loop (Hsu and Vucetic, 2002)

Figure 8 shows two relationships, one between G_s and γ_c and the other between λ and γ_c, for 47 different soils consolidated prior to cyclic shearing to different σ_v (Hsu and Vucetic, 2002). The data also include different levels of frequency, f, and magnitudes of θ. From this pool of data many behavioral trends have been derived, some of which are presented below.

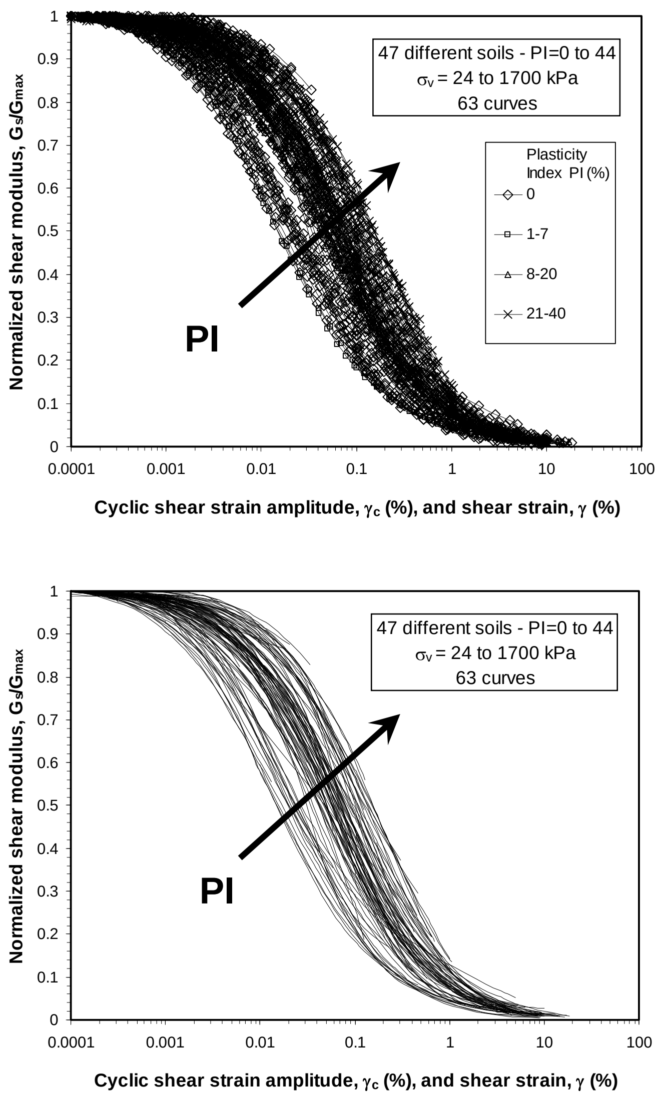

Fig. 9. Normalized secant shear modulus reduction curves derived from the data points presented above in Fig. 8a using routines incorporated in the database (Hsu and Vucetic, 2002

From the data in Fig. 8a the secant shear modulus reduction curves, G_s–logγ_c, for the same soils were constructed, the corresponding values of G_{max} were then estimated by extrapolation, and the corresponding normalized secant shear modulus reduction curves, G_s/G_{max}–logγ_c, derived. The 63 normalized secant shear modulus reduction curves, G_s/G_{max}–logγ_c, obtained in this way are presented in Fig. 9. The figure shows how the curves plot higher as PI of the soil increases, which is the recognized trend of this curves (Kokusho et al., 1982; Vucetic and Dobry, 1991). In Fig. 10 the λ–logγ_c trend obtained in a similar manner is plotted, showing a recognized trend of the curves plotting lower as PI increases.

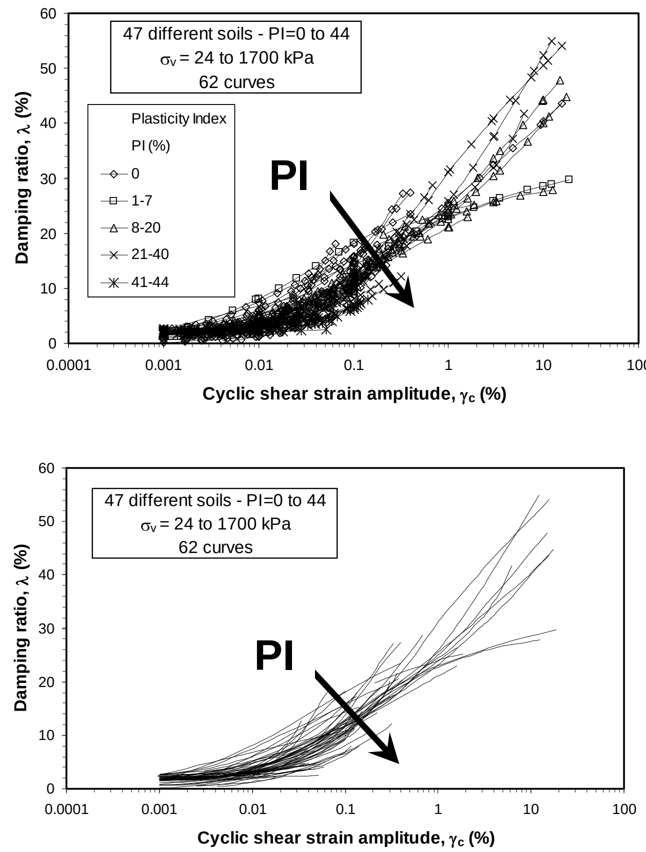

Fig. 10. Equivalent viscous damping ratio curves derived from the data points presented above in Fig. 8b using routines incorporated in the database (Hsu and Vucetic, 2002)

From the data in Fig. 9 that are part of the database, the distributions of the G_s/G_{max} data points with PI for three levels of γ_c have been derived and plotted in Fig. 11 along with the data points obtained earlier by other investigators. This comparisons reveal that the trends obtained earlier for γ_c=0.01% and 0.1% are pretty good and in agreement with new data, while for γ_c=1.0% new G_s/G_{max} data plot more or less around 0.1 and do not show an increase with PI in the range of tested PI from 0 to 40.

In Figs. 12 and 13 there are two types of trends derived rather directly from the database for two groups of soils. First, all of the values of G_s/G_{max} and λ for nonplastic cohesionless sandy and silty soils (labeled as the PI=0 soils), and the clayey soils having PI between 31 and 44, were extracted from the database. These data were then automatically separated in groups corresponding to γ_c=0.001, 0.01, 0.1, 1.0, 3.0, and 10.0% and plotted versus vertical consolidation stress, σ_v. In this way the presented effects of σ_v on G_s/G_{max} and λ at different levels of γ_c are obtained.

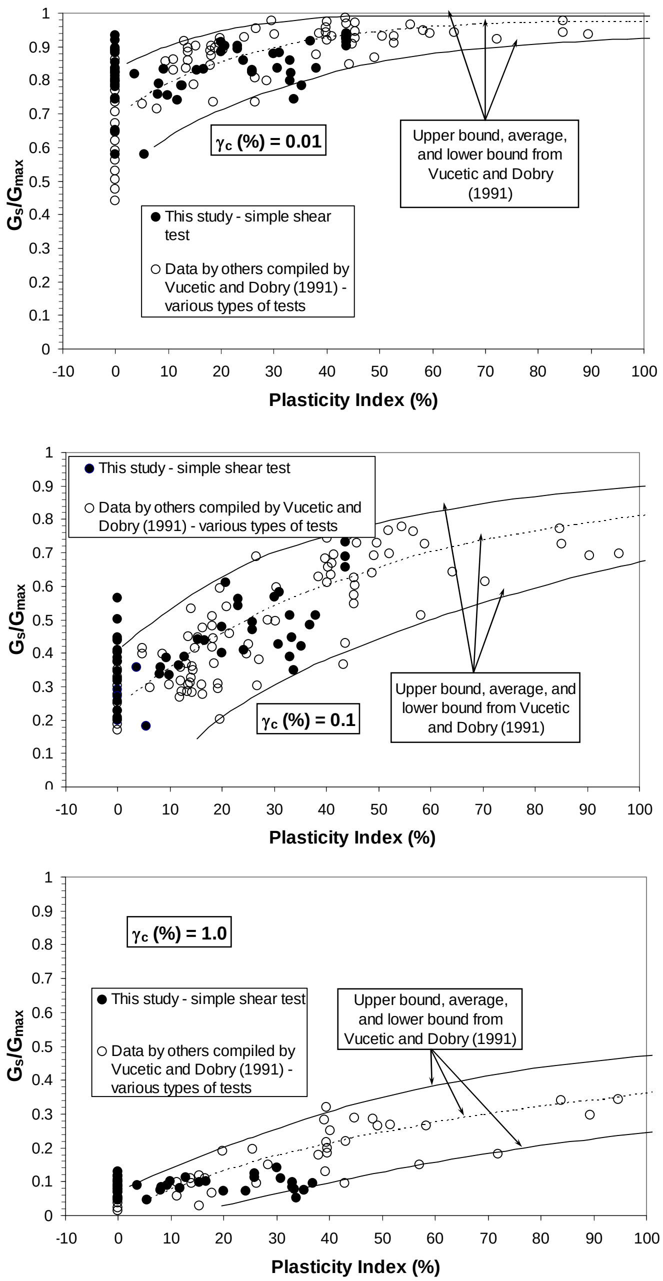

Fig.11. Distribution of the normalized secant shear modulus data points with soil's plasticity index for three cyclic shear strain amplitudes (Hsu and Vucetic, 2002)

From the average trends plotted in Figs. 12 and 13 the charts in Figs. 14 and 15 are derived, showing the effect of σ_v on G_s/G_{max} and λ curves.

In Fig. 16 is an example of the analysis of the DSDSS test results on kaolinite clay (PI=20, σ'_{vc}=300 kPa, OCR=1) extracted from the database. The corresponding tests were aimed at investigating the effect of cyclic frequency, f, on the secant shear modulus, G_s, and damping ratio, λ. The G_s and λ data were first separated into groups corresponding to certain narrow ranges of γ_c and then plotted against corresponding frequencies.

The last example of the analysis of the cyclic data incorporated into the database is presented in Fig. 17. It shows how different data in the database pertaining to a selected soil are crossplotted to obtain interesting trends. The single chart in Fig. 17 shows how damping ratio, λ, is influenced by vertical consolidation stress and the average strain rate defined as $\dot{\gamma}$ =4 γ_cf.

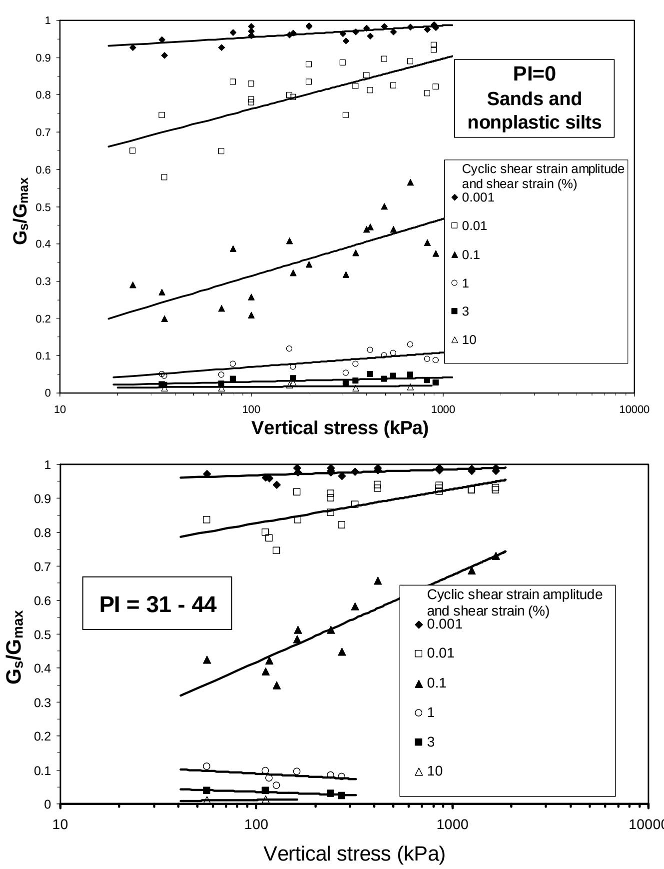

Fig.12. Variation of normalized secant shear modulus, G_s/G_{max}, with vertical stress, σ_v, for two groups of soils derived from the database – each data point pertains to a cyclic loop (Hsu and Vucetic, 2002)

FINAL REMARKS

This paper provides just a brief description of the database of cyclic soil properties created at UCLA from more than 120 direct simple shear tests on more than 60 soils. More about it can be found in Hsu and Vucetic (2002). The elementary unit of the database is the cyclic loop. In the database each cyclic loop is assigned a series of properties. They are the plasticity index of the soil, void ratio, moisture content, degree of saturation, vertical stress prior to cycling, overconsolidation ratio, cyclic shear strain amplitude, frequency of cyclic loading, secant shear modulus, shape of cyclic straining, and damping ratio. The database also contains procedures for comparing and analyzing the data so that it can be used to generate various correlations and trends between different data. Several examples of such correlations and trends are presented above and many more can be found in Hsu and Vucetic (2002), Matesic and Vucetic (2003) and some other publications listed below.

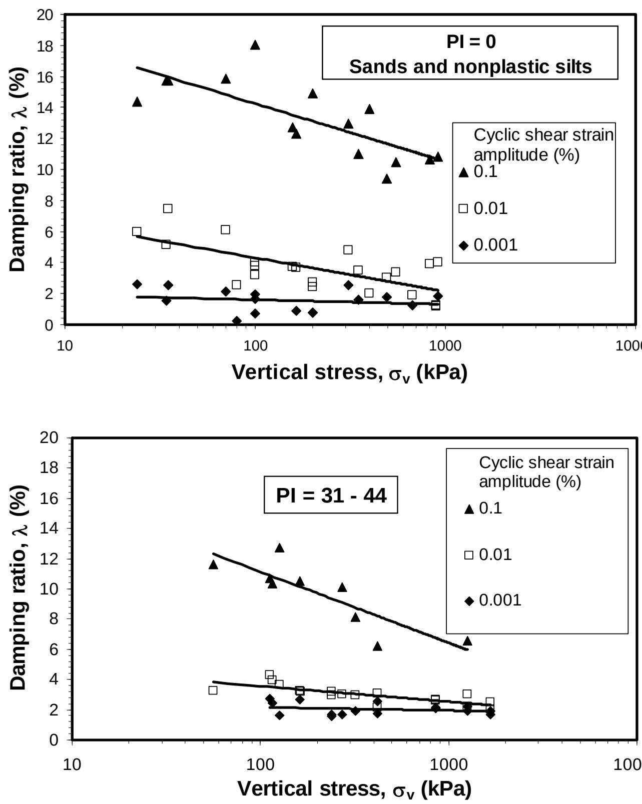

Fig.13. Variation of damping ratio, λ, with vertical stress, σ_v, for two groups of soils derived from the database – each data point pertains to a cyclic loop (Hsu and Vucetic, 2002)

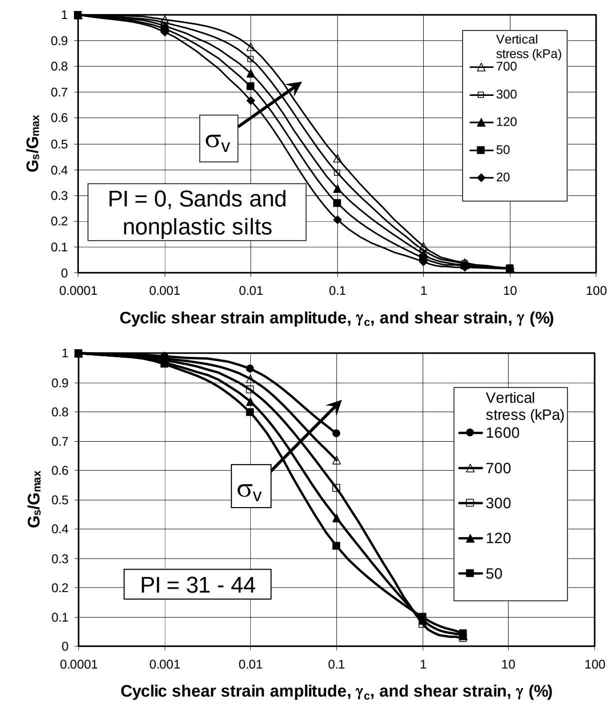

Fig. 14. Effect of vertical stress on the normalized secant shear modulus reduction curve for two groups of soils derived from Fig. 12 above (Hsu and Vucetic, 2002)

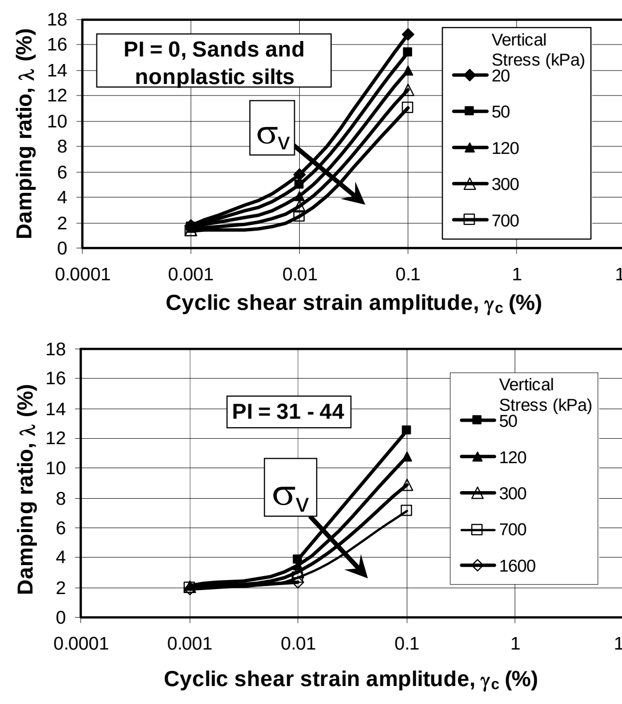

Fig. 15. Effect of vertical stress on the equivalent viscous damping ratio curve for two groups of soils derived from Fig. 13 above (Hsu and Vucetic, 2002)

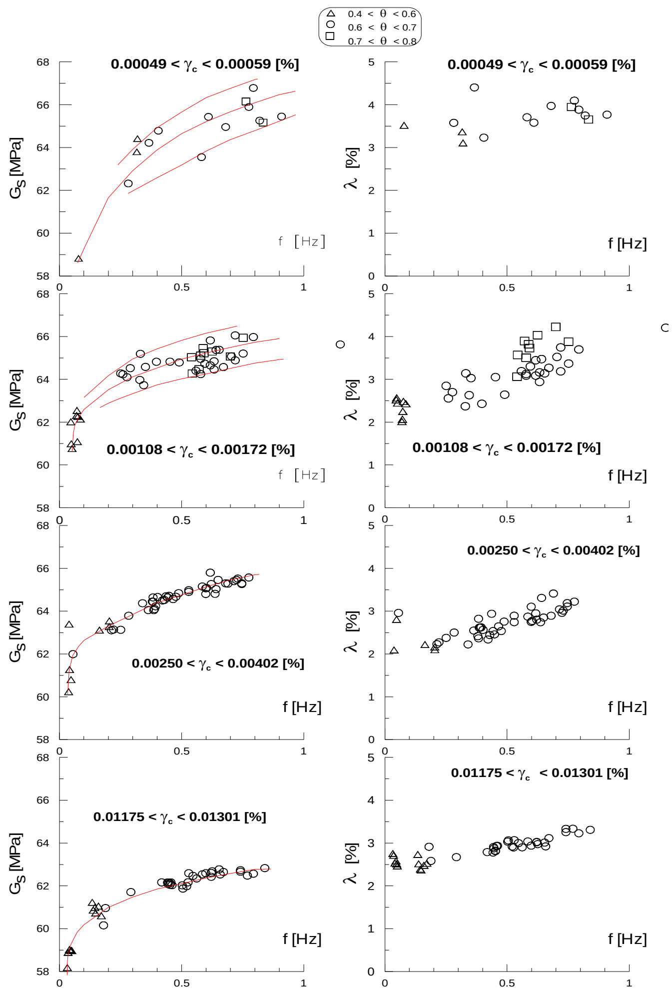

Fig. 16. Example of the analysis of the DSDSS test results on kaolinite clay (PI=20, σ'_{vc}=300 kPa, OCR=1) incorporated into the database and aimed at investigating the effect of cyclic frequency, f, on secant shear modulus, G_s, and damping ratio, λ (data treated in Matesic and Vucetic, 2003)

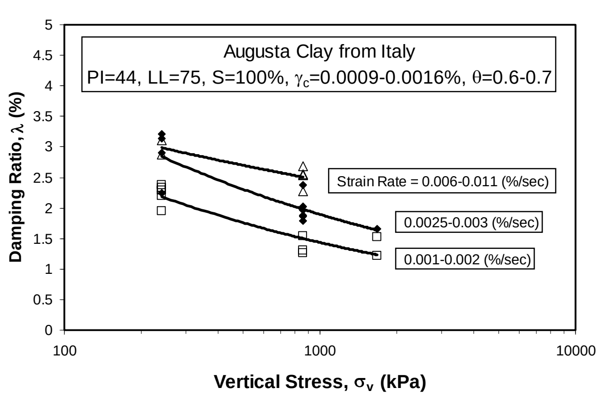

Fig. 17. Variation of λ with σ_v and average strain rate, $\dot{\gamma}$, at small γ_c for a highly plastic clay derived directly from the database (Hsu and Vucetic, 2002)

REFERENCES

Bjerrum, L. and Landva, A. [1966]. “Direct Simple-Shear Test on a Norwegian Quick Clay”, *Géotechnique*, 16(1), 1-20.

Dobry, R., Ladd, R.S., Yokel, F.Y., Chung, R.M., and Powell, D. [1982]. “Prediction of Pore Water Pressure Buildup and Liquefaction of Sands During Earthquakes by the Cyclic Strain Method.” *National Bureau of Standards Building Science Series 138*, July 1982, 150 pp.

Doroudian, M., and Vucetic, M. [1995]. “A direct simple shear device for measuring small-strain behavior”, *ASTM Geotechnical Testing Journal*, GTJODJ, Vol. 18, No. 1, pp. 69-85.

Doroudian, M. and Vucetic, M. [1998]. "Small-Strain Testing in an NGI-type Direct Simple Shear Device," *Proceedings of the 11th Danube-European Conference on Soil Mechanics and Geotechnical Engineering*, Porec, Croatia, Publisher A.A. Balkema, pp. 687-693.

Doroudian, M. and Vucetic, M. [1999]. “Results of geotechnical laboratory tests on soil samples from the UC Santa Barbara Campus”, Report for the University of California’s Campus - Laboratory Collaboration (CLC) Program Research Project ‘Estimation of the Ground Motion Exposure from Large Earthquakes at Four UC Campuses in Southern California’, *UCLA Research Report* No. ENG-99-203, Civil and Environmental Eng. Department, University of California, Los Angeles, CA, April, 107p.

Hsu, C-C., and Vucetic, M. [1998]. “Results of classification tests for ROSRINE project”, *UCLA Research Report*, No. ENG-98-199, Civil and Environmental Engineering Department, University of California, Los Angeles, CA, December, 260p.

Hsu, C-C., and Vucetic, M. [1999]. “Results of cyclic and dynamic simple shear tests on soils from Tarzana and Rinaldi sites conducted for ROSRINE project and other research purposes”, *UCLA Research Report* No. ENG-99-205, Civil and Environmental Engineering Department, University of California, Los Angeles, CA, June, 263 p.

Hsu, C-C., and Vucetic, M. [2002]. “Dynamic and Cyclic Behavior of Soils Over the Wide Range of Shear Strains in NGI-type Simple Shear Testing Devices", *UCLA Research Report* No. ENG-02-228, Civil and Environmental Engineering Department, University of California, Los Angeles, Dec., 267 p.

Hsu, C-C. and Vucetic, M. [2004]. “Volumetric Threshold Shear Strain for Cyclic Settlement”, *ASCE Journal of Geotechnical and Geoenvironmental Engineering*, Vol. 130, No. 1, pp. 58-70.

Hsu, C-C. and Vucetic, M. [2006] “Threshold Shear Strain for Cyclic Pore-Water Pressure in Cohesive Soils”, *ASCE Journal of Geotechnical and Geoenvironmental Engineering*, Vol. 132, No. 10, pp. 1325-1335.

Kokusho, T., Y. Yoshida, and Y. Esashi [1982]. “Dynamic properties of soft clay for wide strain range”, *Soils and Foundations* 22(4):1-18.

Matesic, L. and Vucetic, M. [1998]. “Results of geotechnical laboratory tests on soil samples from the UC Riverside Campus”, Report for the University of California’s Campus - Laboratory Collaboration (CLC) Program Research Project ‘Estimation of the Ground Motion Exposure from Large Earthquakes at Four UC Campuses in Southern California’, *UCLA Research Report* No. ENG-98-198, Civil and Environmental Engineering Department, University of California, Los Angeles, CA, November, 218 p.

Matesic, L. & Vucetic, M. [2003]. “Strain-Rate Effect on Soil Secant Shear Modulus at Small Cyclic Strains,” *ASCE Journal of Geotechnical and Geoenvironmental Engineering*, Vol. 129, No. 6, pp, 536-549.

Tabata, K., and Vucetic, M. [2000]. “Results of cyclic simple shear tests on thirteen soils from Los Angeles basin conducted for ROSRINE project and other research purposes”, *UCLA Research Report* No. ENG-00-219, Civil and Environmental Engineering Department, University of California, Los Angeles, CA, December, 283 p.

Tabata, K., and Vucetic, M. [2002]. “Results of cyclic simple shear tests on fifteen soils conducted for PEARL project and other research purposes”, *UCLA Research Report* No. ENG-02-233, Civil and Environmental Engineering Department, University of California, Los Angeles, CA, November, 344 p.

Vucetic, M., [1994]. "Cyclic Threshold Shear Strains in Soils," *ASCE Journal of Geotechnical Engineering*, Vol. 120, No. 12, pp. 2208-2228.

Vucetic, M. [2000]. “Results of cyclic simple shear tests on soil samples from Imperial Valey, Desert Hot Springs, North Palm Springs and Corralitos sites conducted for the NEAR-FIELD Earthquake Project”, *Consulting Research Report* to GEOVision Geophysical Services (Corona, CA) for Kajima Corporation (Tokyo, Japan), Los Angeles. CA, October, 135 p.

Vucetic, M. and Dobry, R. [1991]. "Effect of Soil Plasticity on Cyclic Response," *ASCE Journal of Geotechnical Engineering*, Vol. 117, No. 1, pp. 89-107.

Vucetic, M., Doroudian, M. and Matesic, L. [1999]. “Results of geotechnical laboratory tests on soil samples from the UC San Diego Campus”, Report for the University of California’s Campus - Laboratory Collaboration (CLC) Program Research Project ‘Estimation of the Ground Motion Exposure from Large Earthquakes at Four UC Campuses in Southern California’, *UCLA Research Report* No.. ENG-99-204, Civil and Environmental Eng. Department, University of California, Los Angeles, CA, May, 110p.

Vucetic, M., Hsu, C-C., and Doroudian, M. [1998]. “Results of cyclic and dynamic simple shear tests on soils from La Cienega site conducted for ROSRINE project and other research purposes”, *UCLA Research Report* No. ENG-98-200, Civil and Environmental Engineering Department, University of California, CA, Los Angeles, December, 440 p.

Vucetic, M., Lanzo, G., and Doroudian, M. [1998]. “Effect of the Shape of Cyclic Loading on Damping Ratio at Small Strains”, *Soils and Foundations*, Vol. 38, No. 1, pp. 111-120.

Vucetic, M. and Tabata, K. [2003]. “Influence of Soil Type on the Effect of Strain Rate on Small-strain Cyclic Shear Modulus”, *Soils and Foundation,* Vol. 43, No. 5, pp. 161-173.

Vucetic, M, Tabata, K. and Matesic, L [2003]. “Effect of Average Straining Rate on Shear Modulus at Small Cyclic Strains” *Proceedings, International Conference “Deformation Characteristics of Geomaterials”,* Lyon, 2003*”,* Editors: Di Benedetto et al., Publisher: A.A., Balkema, Lisse, pp. 321-328.