LABORATORY INVESTIGATION FOR ESTIMATION THE SEISMIC RESPONSE OF GROUND

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ABSTRACT

Laboratory measurements of soil properties can be used to supplement or confirm the results of field measurements. They are necessary to establish values of damping and modulus at strains larger than those that can be obtained in the field or to measure the properties of materials that do not exist in the nature. The Dynamic Deformation Characteristics of the soil are used in order to calculate seismic response of ground, earth structures and structure-ground response. To obtain the dynamic proprieties of the soil we used improved cyclic triaxial equipment that is also used to express phenomenon that make soil to fail under seismic loading. The upgrade of the equipment after the training period in Japan at BRI, Tokyo Soil and Tokyo University and during the counterpart JICA program improved the quality of the obtained results.

INTRODUCTION

The equipments for dynamic laboratory soil testing at National Center for Seismic Risk Reduction Bucharest Romania (NCSRR) consist of triaxial testing equipment, data acquisition and processing systems made by Seiken, Japan. Starting to 2003, NCSRR received all those equipments, as a donation from Japan International Cooperation Agency (JICA) through the Technical Cooperation Project on the Reduction of Seismic Risk for Buildings and Structures in Romania.

In designing of engineering structures, when a field seismic investigation is conducted, the dynamic proprieties of the soil must be obtained. A large number of laboratory tests for dynamic purposes have been developed, and research continues in this area. These tests can generally be classified into two groups: those that apply dynamic loads and those that apply loads that are cyclic but slow enough that inertial effects do not occur. The most widely used of the cyclic loading laboratory tests is the cyclic triaxial test. Cyclic load is usually applied as cyclic axial load by mechanical, hydraulic or pneumatic actuator. In this test a cyclic load is applied to a column of soil over a number of cycles. The response of load is observed, and the test is repeated at a higher load.

TRIAXIAL EQUIPMENT AT NCSRR

In July 2003 at NCSRR was installed the triaxial equipment. Seiken Inc. Japan made the equipment and the commissioning. The equipment fulfils all the requirements of The Japanese Geotechnical Society, 2000.

The NCSRR triaxial equipment, Figure 1, can solve the following types of problems:

- Static problems with strain level at 10^{-3} or greater (the main concern regarding the static problems is used to evaluate the degree of safety of foundations or soil structure against the failure);

- Dynamic problems with soils subjected to a strain levels as small as 10^{-6} (used to evaluate the soil strength in comparison with stresses induced by external loading and the settlement of ground or structures associated with the deformation of soils.

Specifications of the triaxial equipment

1. Triaxial Cell

1) Air bushed piston of extremely small friction
2) Specimen Size: Diameter 50mm × 100mm

Technical University of Civil Engineering, Bucharest (UTCB)

3) Lateral Pressure Capacity: Max. 1Mpa
4) Axial Loading Capacity: 5kN (Equipped with Water-proof and Pressure-proof Load cell 3kN)

2. Vertical Pressure Loading Unit with Air & Water Panel

1) Static Vertical Loading: Electric Strain Control by Mechanical jack, Capacity 5kN, (0.002 – 2 mm/min. Step-less variable type)
2) Dynamic Vertical Loading: Stress Control by Pneumatic bellofram cylinder, Capacity 2kN
3) Lateral & Back Pressure Loads: Both 0 – 1Mpa by Air regulators, Manual operation
4) Volume Change Apparatus: Double tube burette type 25ml
5) Master Gauge: Dia.200 ×1Mpa, Min. div. 1/500

3. Pneumatic Sine Loader

1) Electric-Pneumatic pressure conversion type & Loading control type
2) Range of Vibration: 0.001 – 2 Hz
3) Loading Wave: Sine wave
4) Setting of Load: Both Static Bias & Dynamic loading are 1000 Division, Potentiometer type
5) Loading Number of Times: Random Preset type with 6 Figures Digital Counter
6) Pneumatic Pressure Capacity: 1Mpa
7) Electric Power Source: AC Single phase local voltage

4. Transducers & Amplifiers

1) Inner Load Cell: 2kN or 500N
2) Large Vertical Displacement Transducer: 25mm
3) Pore Water Pressure Transducer: 1Mpa
4) Small Vertical Displacement Transducers (gap sensors) max. +/- 1mm & Amplifiers
5) Lateral Pressure Transducer: 1Mpa
6) Volume Change Transducer: 25ml
7) Amplifiers suitable for the above transducers.

Fig. 1 Triaxial Testing Apparatus Model DTC-367 by Seiken.Inc. Japan (Photo at NCSRR)

The automatic stress strain path control and monitoring for triaxial test is as follows (Fig. 2):

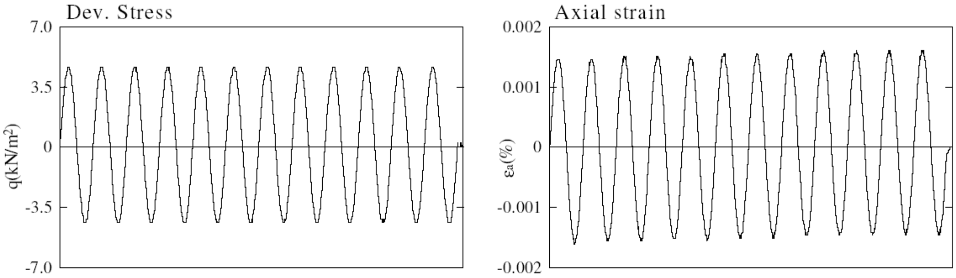


Fig. 2. Example of monitoring of axial pressure and axial cyclic deformation

1. For lateral loading is use a pneumatic pressuring system. An air pump and a servo EP transducer make possible the accurate control of the air-pressure.

2. For axial loading it is important to have a high resolution as well as a large stroke of axial displacement. We use a servo-pneumatic loading system.

3. For very small vertical displacements a pair of gap sensors are used

Loading pattern of the NCSRR laboratory

The loading pattern used at NCSRR laboratory might be:

1. Monotonic loading tests can be conducted with varying speed of loading. The conventional static loading tests employ a rate of loading to failure on the order of few minutes. The monotonic loading test conducted in less than a few seconds to failure are classified as rapid loading tests. Example – evaluate the strength of soil under exhibited blast loading (detonation, bombs).

2. Cyclic load application following the static monotonic loading (example – evaluate the strength of soils during the earthquakes). The initial phase of the static monotonic shear stress application representing a sustained pre-earthquake state of stress which exists in a soil element. The phase of loading is considered as simulating the cyclic shear stress application during the earthquakes.

3. Cyclic monotonic loading is performed firstly to investigate the effects on strength and stiffness deterioration of soils due to seismic shaking. Static properties are changed from the initial values (example – post-stability analysis of dams and embankments).

4. Monotonically increasing cyclic loading – to study the static strength of soil while is being subjected to vibrations.

The difference between static and dynamic loading conditions is in the term of time of loading and is expressed in terms of speed of loading or rate of straining (speed effect or rate effect). The “Time of loading” is defined as ¼ of the period at which the load is reciprocated. If load application last more than 0.1 sec then we have “static problems” and if load application have a shorter time of application we have “dynamic problems”. In Table 1 are presented the description of real loading and consequently the simulation in the laboratory.

Table 1. Simulation of natural or artificial phenomenon in the laboratory tests

Number of cycles	Phenomenon	Duration of loading	Effect
1	Dropping bombs or blasting	$10^{-3} - 10^{-2}$ seconds	Impulse or shock load
10 – 20 with different amplitudes	Earthquakes (the period of each impulse is between 0.1 to 3 seconds)	0.02 – 1 seconds	
100 – 1000	Pile driving, vibro-compaction	Frequency of the loads 10 – 60 Hz	
10^4 - 10^5	Machine foundation (for compressors, electric generator)	Frequency of the loads 10 – 60 Hz	
Very large	Parking, water waves, pavements of railroads,	0.1 – few seconds	Fatigue Repetition effect

CYCLIC UNDRAINED TRIAXIAL TEST ON SOILS

In the engineering approach the earthquake wave travels from the fault to the ground surface though the seismic bedrock where earthquake motion can be defined to be a function with respect to the distance from the fault, and the engineering seismic base layer at which earthquake motion is not affected by the existence of the surface ground, i.e., the subsoil above the engineering seismic base layer. The schematic wave propagation from the earthquake source to the ground surface is drawn in Figure 3. The earthquake wave propagates vertically in the surface ground because the ground becomes softer to the ground surface. In addition, since the soil is soft, it may exhibit nonlinear behavior under the large earthquake. The nonlinear behavior of the surface ground is caused by the vertically propagating of S-wave. The amplification of the surface ground has two characteristics that work in opposite way. The first one is amplification. Since S-wave velocity becomes smaller to the ground surface, energy accumulates resulting in amplification. Therefore as the ground becomes softer, amplification of the wave becomes larger. The other is deamplification. Shear strength decreases as the ground becomes softer, which indicates peak acceleration becomes smaller at softer ground. These two characteristics indicate that, amplification occurs under the small ground shaking, but amplification becomes small as the ground shaking becomes large.

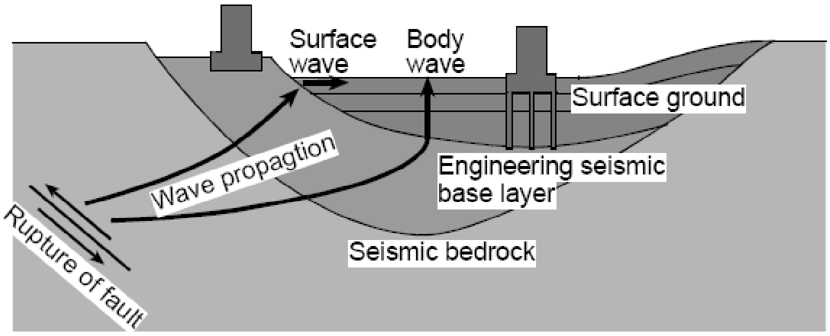


Fig. 3. Schematic wave propagation from the earthquake source to the ground surface (Yoshida. & Iai, 1998)

The 2nd type of CNRRS loading pattern is commonly used to determine the strength of soils under seismic loading conditions. A specimen is consolidated first and subjected to the initial stress σ_S. A sequence of prescribed shear stress cycles is then applied to the test specimen with relatively small amplitude. When the points reached at the end of each sequences are connected in the plot of the stress-strain diagram, Figure 2. Axial stress is the stress applied in the axial direction of the specimen, while lateral stress is the stress applied in the radial direction of the specimen. The difference in these stresses during the cyclic undrained loading process is defined as cyclic deviator stress. All the stress values are computed at the mid-point of the height of the specimen.

This test method covers the determination of the relationships between the single amplitude of cyclic deviator stress or the cyclic stress ratio, which is applied under undrained condition with cyclic triaxial apparatus, and the number of cycles required to cause a specified value of double amplitude of axial strain or to cause a specified value of excess pore water pressure ratio.

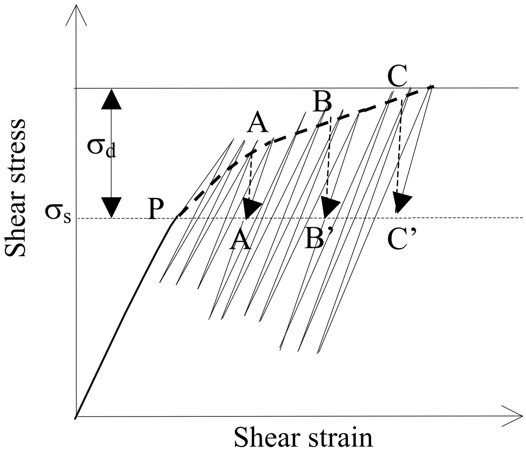
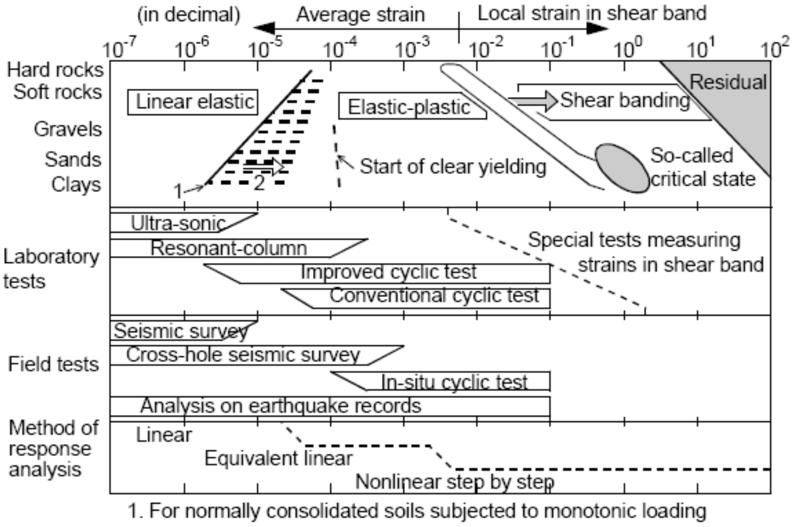


Fig. 4. Construction of a shear stress versus residual curve from multistage loading test results

Low amplitude moduli obtained from cyclic triaxial test

Though soil deformation under seismic loading is relatively small, its modulus is dependent on dynamic stress or strain level. Soil moduli such as Young's modulus and shear modulus decrease as the level of stress or strain increases. Therefore nonlinearity of dynamic deformation characteristics is significant in seismic response analysis. All the soil moduli E, ν, G, h depends on strain range but the dependency of ν is considered rather small. In Figure 5 is shown the methods of measurement and response analysis of soil moduli. The evaluation of shear modulus of soils at very small levels of strains was a main concern of researchers. This modulus is called maximum shear modulus, initial shear modulus, or low amplitude shear modulus and is noted by G_{max} or G_0. It is the custom to take the strain amplitude of $\gamma_a=10^{-5}$ for defining the low-amplitude shear modulus G_0. To obtain a 10^{-4} – 10^{-5} axial strain we must use a very small deviator stress.

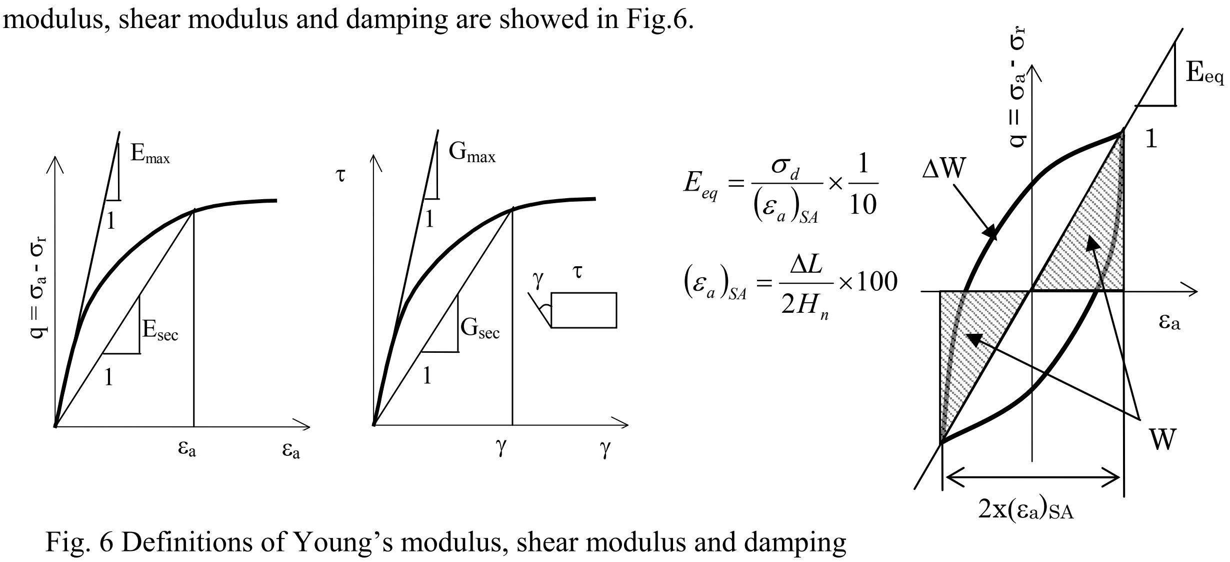


1. For normally consolidated soils subjected to monotonic loading
2. Increases as OCR increases and with cyclic loading

Fig. 5. Strain dependent soil properties, measurement, and analysis (Tatsuoka & Shibuya 1991)

Procedure to calculate the dynamic deformation characteristics

The G- γ (E - γ) and h - γ relationships obtained in DDC (dynamic deformation characteristics tests) are generally recognized to express the deformation characteristics of soil. The definitions of Young's modulus, shear modulus and damping are showed in Fig.6.



$$E_{eq}=\frac{\sigma_d}{(\varepsilon_a)_{SA}}\times\frac{1}{10}$$

$$(\varepsilon_a)_{SA}=\frac{\Delta L}{2H_n}\times 100$$

Fig. 6 Definitions of Young's modulus, shear modulus and damping

The Young's modulus and the hysteretic damping ratio, h (%) are obtained using the following relations:

$$E_{eq} = \frac{\sigma_d}{(\varepsilon_a)_{SA}} \times \frac{1}{10} \text{ and } h = \frac{1}{2\pi} \cdot \frac{\Delta W}{W} \times 100$$

where

σ_d is cyclic stress amplitude (cyclic deviator stress)

$(\varepsilon_a)_{SA}$ is single amplitude cyclic axial strain

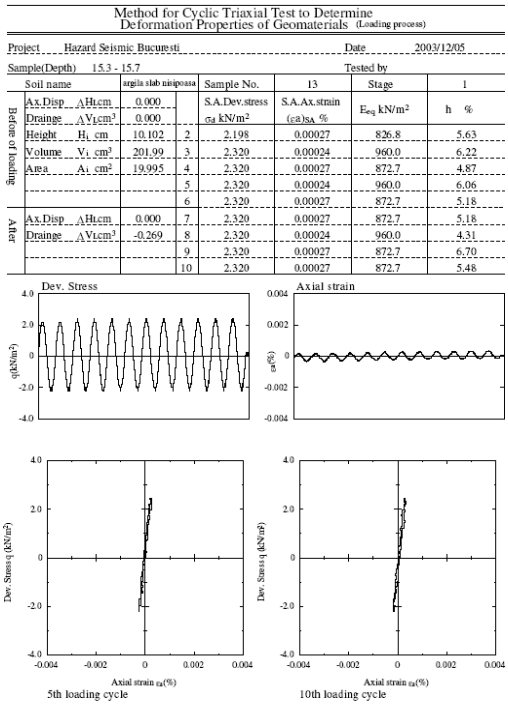
ΔW: damping energy in a single loading cycle, which is defined as the area of the hysteretic loop on the deviator load, versus axial displacement curve

W: equivalent elastic energy input in a single cyclic loading

Upgrading of the equipments

Problems related with damping measurements at very small strains

Conducting cyclic triaxial deformation property test with our equipment, unfortunately, sometimes we observed some differences between measured value of the damping and the real ones. The errors of damping calculation at very small strain, $10^{-4} – 10^{-5}$ become for us the most important issue. In Figure 7 is presented an example of an unusual damping value of 5,63%, resulted from calculations, bigger damping than a usual value of 2% corresponding to that very small strain (Arion, 2004).

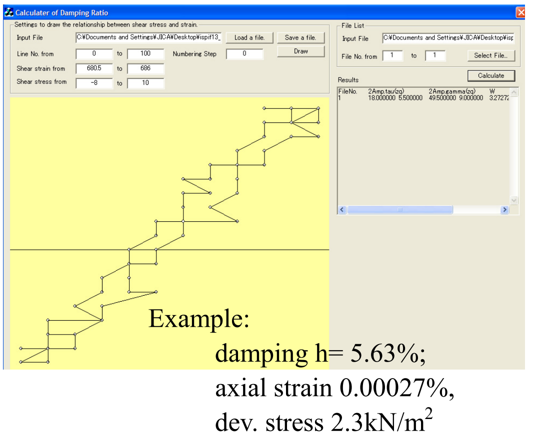


Method for Cyclic Triaxial Test to Determine
Deformation Properties of Geomaterials (Loading process)

Project Hazard Seismic Bucuresti Date 2003/12/05

Sample(Depth) 15.3 - 15.7 Tested by

	Soil name	argila slab nisipoasa		Sample No.	13	Stage	1
Before of loading	Ax.Disp ΔHL cm	0.000		S.A.Dev.stress σ_d kN/m²	S.A.Ax.strain $(\varepsilon a)_{SA}$ %	E_{eq} kN/m²	h %
	Drainge ΔVL cm³	0.000					
	Height Hi cm	10.102	2	2.198	0.00027	826.8	5.63
	Volume Vi cm³	201.99	3	2.320	0.00024	960.0	6.22
	Area Ai cm²	19.995	4	2.320	0.00027	872.7	4.87
			5	2.320	0.00024	960.0	6.06
			6	2.320	0.00027	872.7	5.18
After	Ax.Disp ΔHL cm	0.000	7	2.320	0.00027	872.7	5.18
	Drainge ΔVL cm³	-0.269	8	2.320	0.00024	960.0	4.31
			9	2.320	0.00027	872.7	6.70
			10	2.320	0.00027	872.7	5.48



Settings to draw the relationship between shear stress and strain.

Input File C:¥Documents and Settings¥JICA¥Desktop¥ispif13_

Line No. from 0 to 100 Numbering Step 0

Shear strain from 680.5 to 686

Shear stress from -8 to 10

File List

Input File C:¥Documents and Settings¥JICA¥Desktop¥isp

File No. from 1 to 1

Results

```
FileNo.    2Amp.tau(zq)           2Amp.gamma(zq)         W
1          18.000000  5.500000    49.500000  9.000000    3.27272
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Example:
damping h= 5.63%;
axial strain 0.00027%,
dev. stress 2.3kN/m²

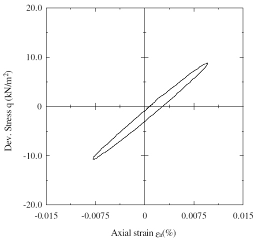

Fig. 7 Example of monitoring of deviator stress and axial strain (left) and verification of the damping and modulus test results using the additional computation (right)

During the training period in Japan, Prof Towhata and Prof Tatsuoka from Tokyo University suggestions about our problems with damping calculation at very small strain might have the following causes:

1. Effects of bedding error at the top and bottom ends of specimen (the deformation of the loading piston and specimen cap);
2. Frequency of loading;
3. Noise of the power supply;
4. Sensitivity of the pickup (output of the pickup) (A/D –converter); 16 bit (2^{16}) or 12bit (2^{12});

5. Time gap: for example 1/100 sec between the force and displacement measurement can increase the damping;

6. Signal/noise ratio – S/N ratio;

7. Cell pressure capacity (bigger – small resolution; small capacity- fine resolution);

8. Type of soil specimen (stiff clay, soft rock – more problems in measurements).

Also during the discussions they recommend the use of LDT type sensors instead of measurement system made with gap sensors. This comment might be questionable.

Upgrading the equipments

From the eight points list we focus especially on a 4th and a 7th. Together with people from SEIKEN INC.(1-28-5, Higashi-Ueno, Taito-ku, Tokyo, 110-0015), Mr. Itoh and Mr. Soyama, and with the financial help from JICA we did the following to the equipment:

- Changed AD board of the triaxial apparatus. A new 16Ch/16Bit High-speed Analog Multi-Function I/O Board was installed to convert analog input signals to digital equivalents (performing analog-to-digital conversion). This card is the high-speed, high precision type that performs A-D conversion at a conversion speed of 1 microsecond per channel and a resolution of 16-bit. The board has buffer memory available as a FIFO or ring buffer to hold 16 megabytes of data. This enables sampling to be executed in the background independently of the processing power of the PC;
- Changed the load cell. The old model of load cell, LP-200 with 2000N capacity was replaced with the new one LP-50, with 500N capacity;
- The new version of the acquisition and processing software and also 2 types of steel springs (for evaluation of the time gap) were forwarded to Romania.

The chosen upgraded solutions for triaxial equipment solve the problems with damping calculation and improve accuracy of data recorded. The results might be observed in Figures 8.

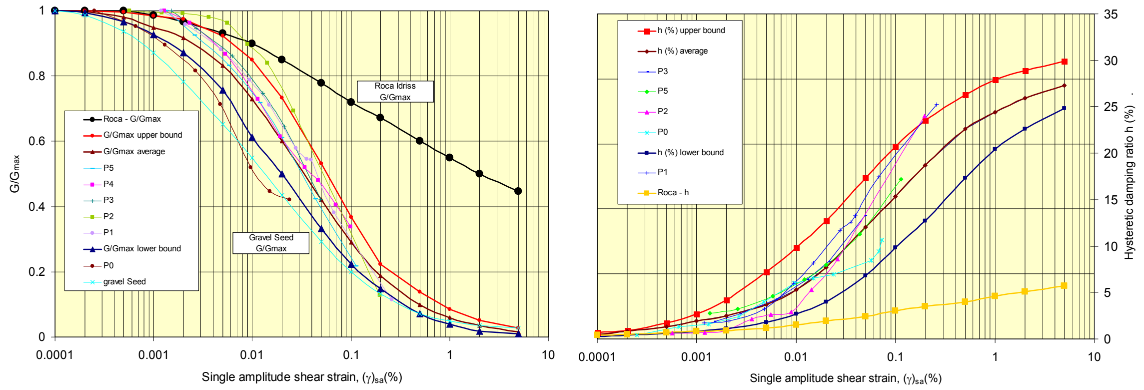

Fig. 8a Test results for sandy soils from Bucharest and comparison with analytical model curves

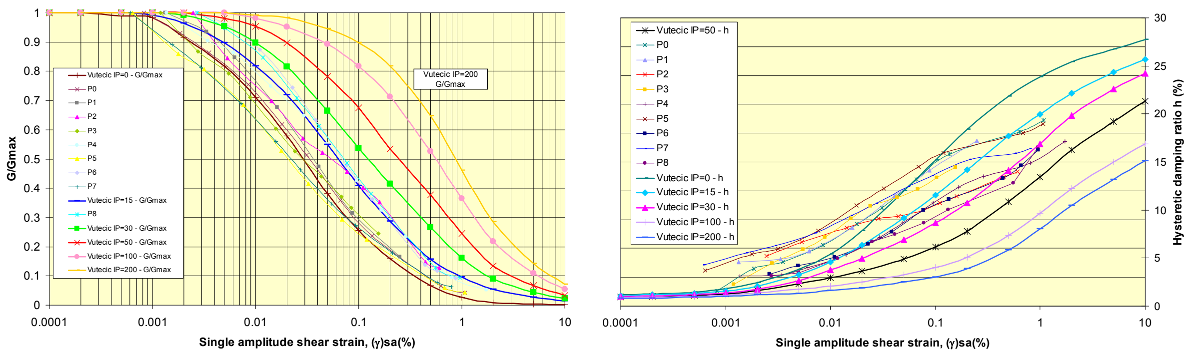

Fig. 8b Test results for cohesive soils from Bucharest and comparison with analytical model curves

Split barrel sampler for clay soils Trimming and preparation of clay sample Shear failure of tested sample

Preservation of soil samples Trimming and preparation of clay sample Shear failure of tested sample

Fig. 9. Sampling, preparation and testing of the soil samples

Results from the tests

During last two years we conduct series of dynamic triaxial tests especially on the clay soils from Bucharest. In the Figures 8a and 8b are represented relations of shear modulus ratio G/G_O versus shear strain and the strain dependent damping for the laboratory samples. Also we represented the strain-dependent modulus and damping curves quoted in the literature (Vucetic & Dobry, 1986). In Figure 9 are presented the steps of preparation of the soils in our laboratory.

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